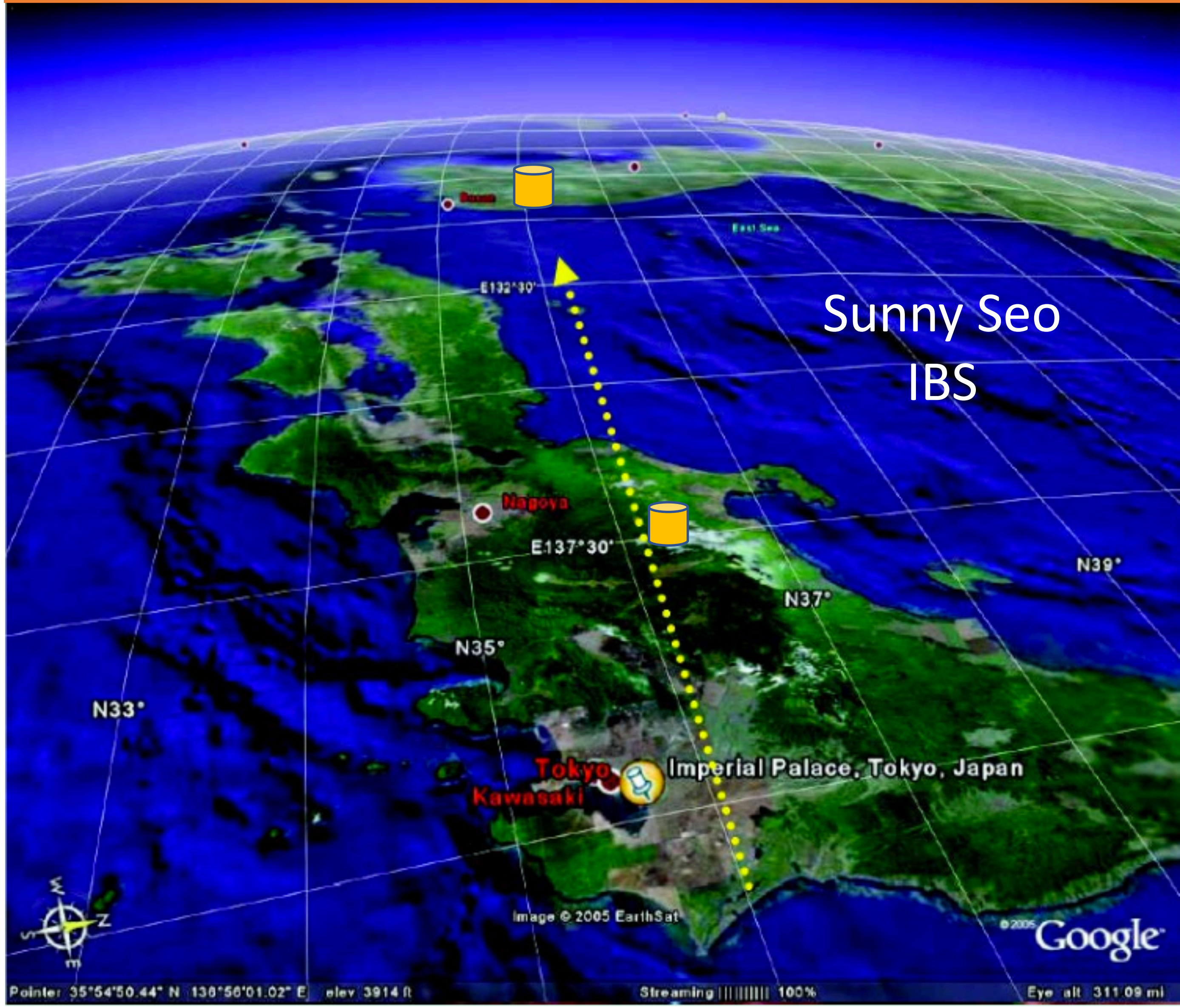
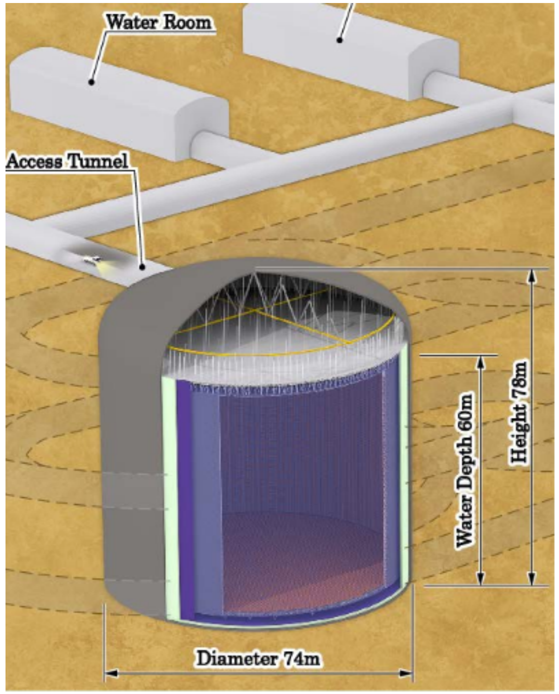
Status of Hyper-K and T2HKK



Sunny Seo
IBS

Hyper-Kamiokande

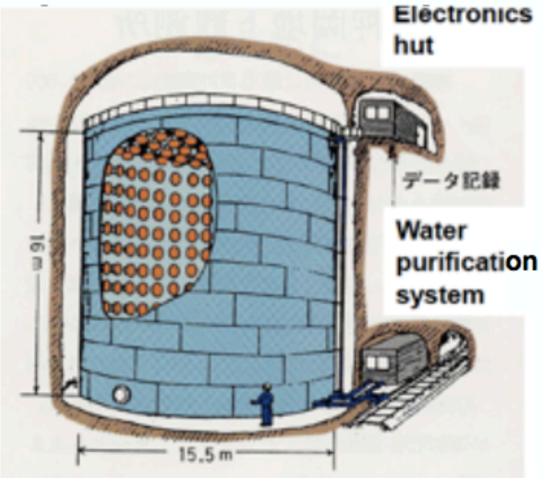


NPC Seminar
Fermilab
2019.08.01

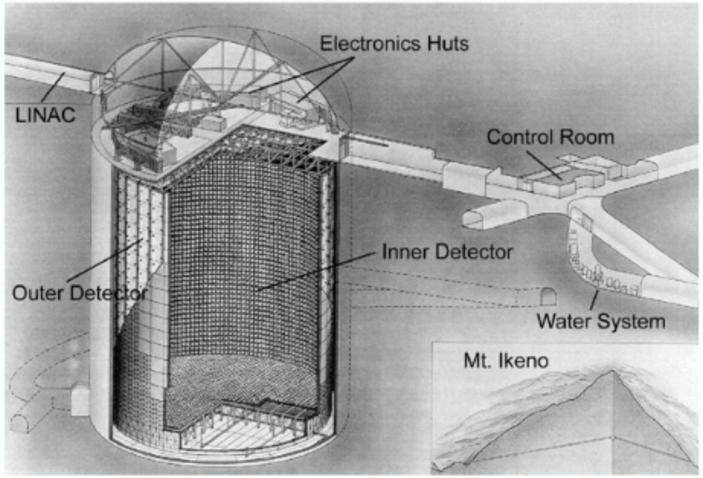
3 Generations of Kamiokande

3,000 ton → 50,000 ton → 2 x 260,000 ton

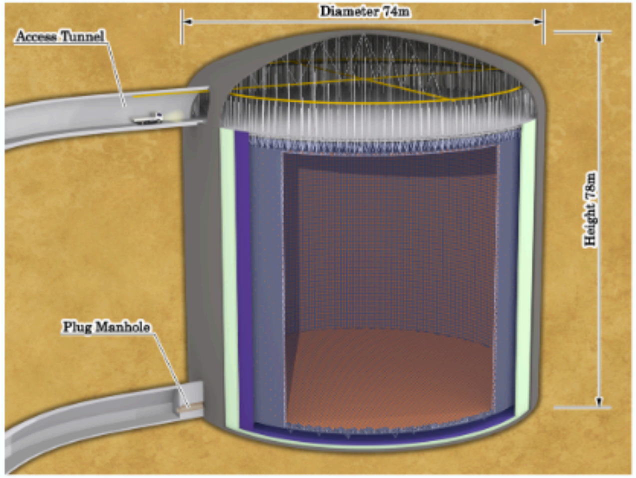
Kamiokande
1983–1996



Super-Kamiokande
1996–today (and beyond)



Hyper-Kamiokande
~2026–???



Koshiba, 2002

SN1987A

→

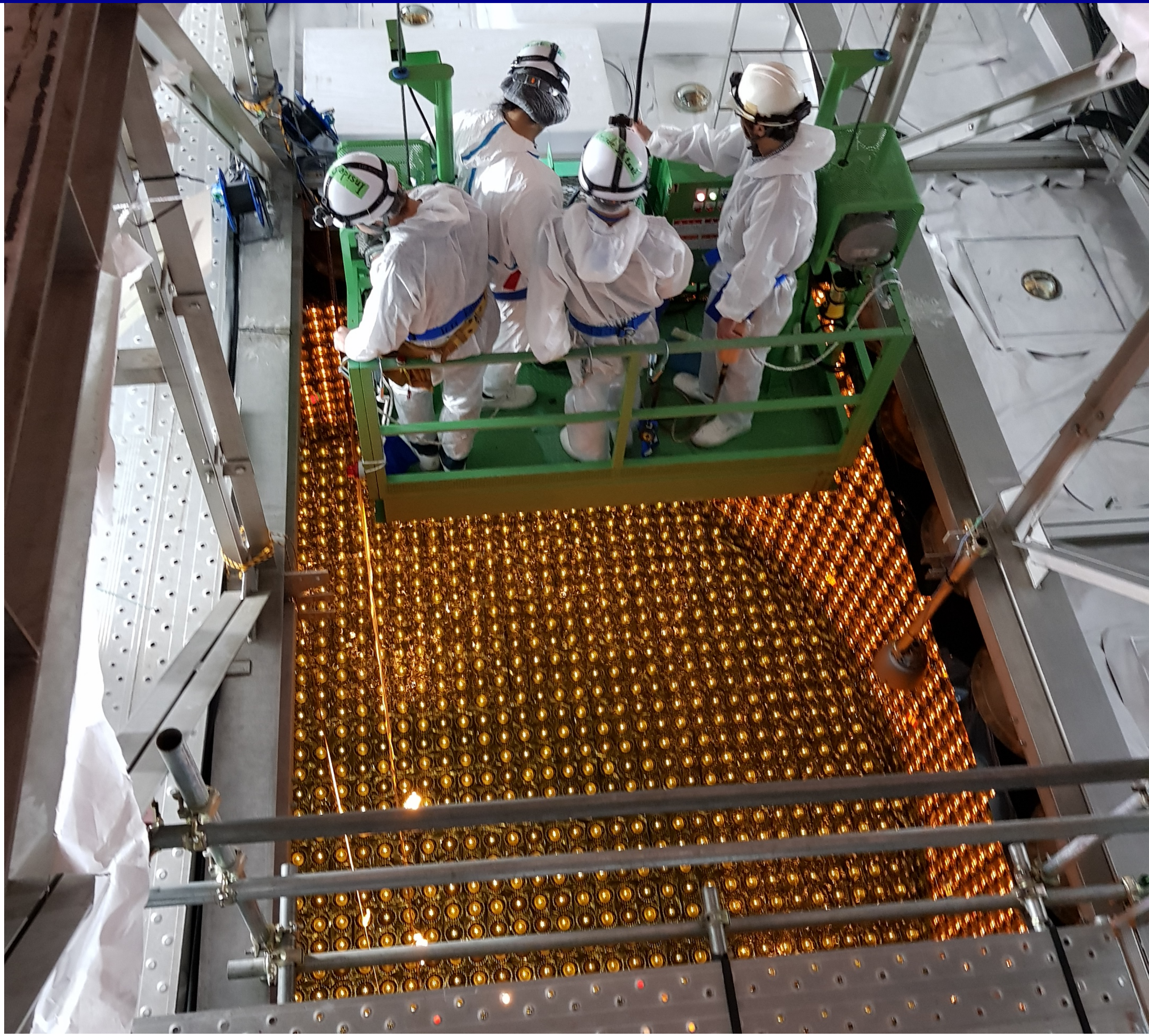
Kajita, 2015

ν oscillation

→

???, 20??

Super-K Tank Open (2018) → SK-Gd



Super-K Tank Open (2018) → SK-Gd

Now, Hyper-K 1st detector major funding from Japan is secured !

Announcement 2018.09.12

→ HK 1st detector construction starts in April 2020.

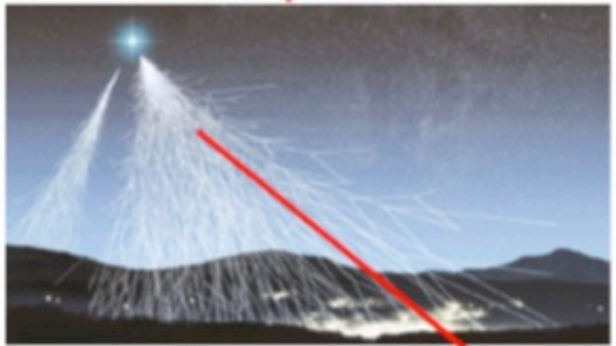
Funding request for the 2nd Korean detector will be proceeded to the Korean government.

International Hyper-K proto-collaboration

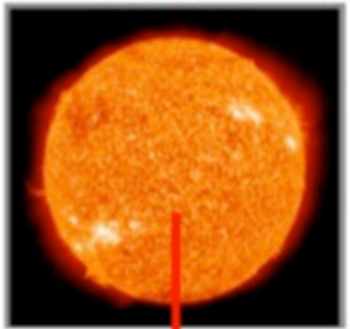
17 countries, ~80 institutes, ~300 members

Hyper-K Physics Program

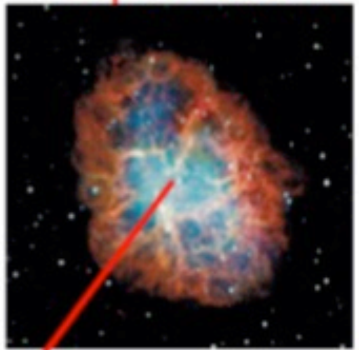
Atmospheric ν



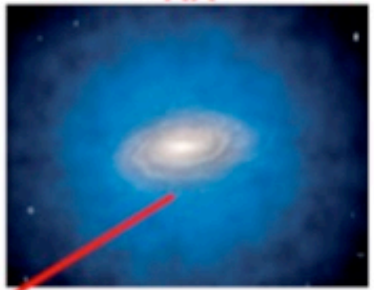
Solar ν



Supernova ν



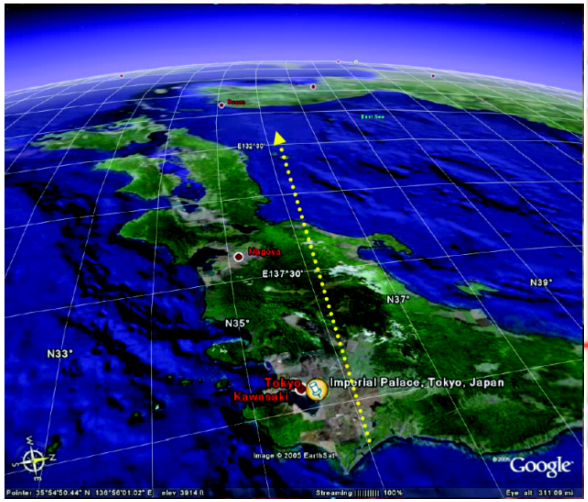
WIMP χχ -> νν

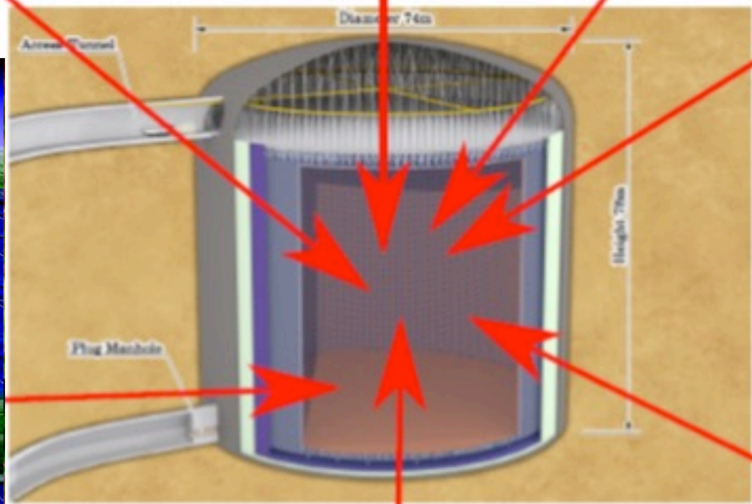


Neutrino oscillation

Neutrino telescope

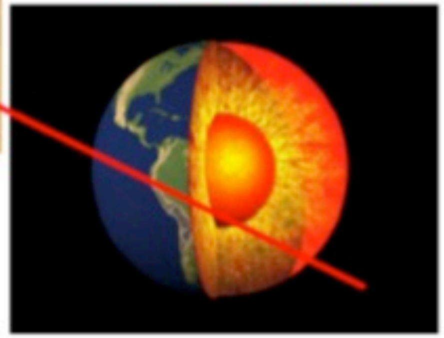
Beam ν



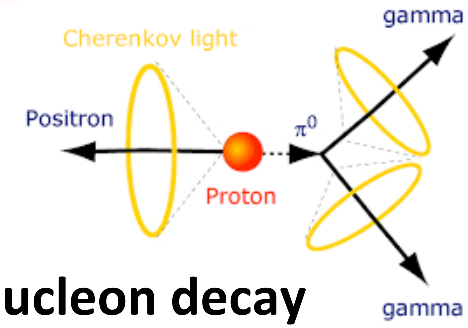


New step to geo-science

ν Tomography



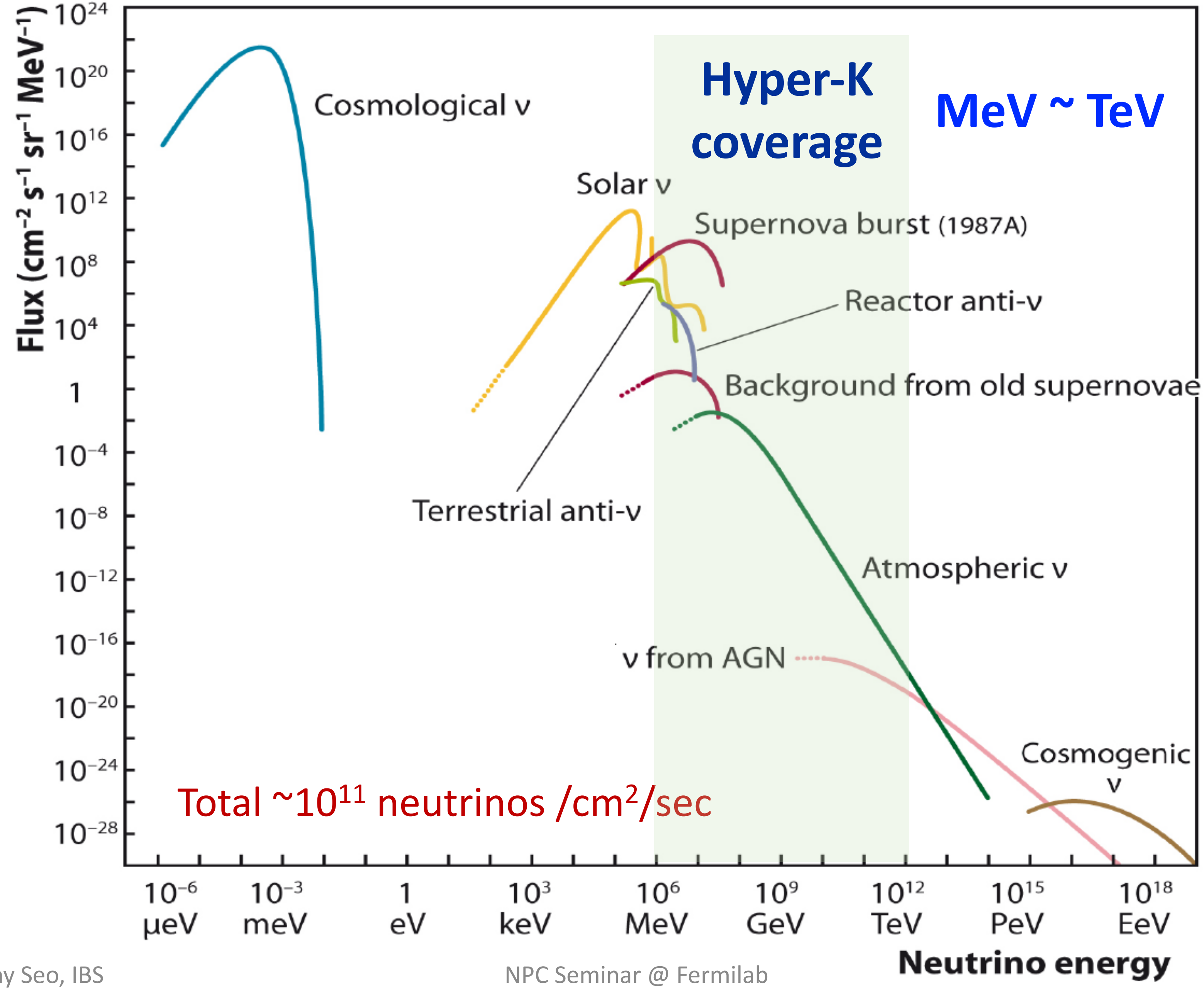
CPV & neutrino mass ordering (MO)



Nucleon decay

Lifetime : 10^{35} yrs

Neutrino Sources & Fluxes

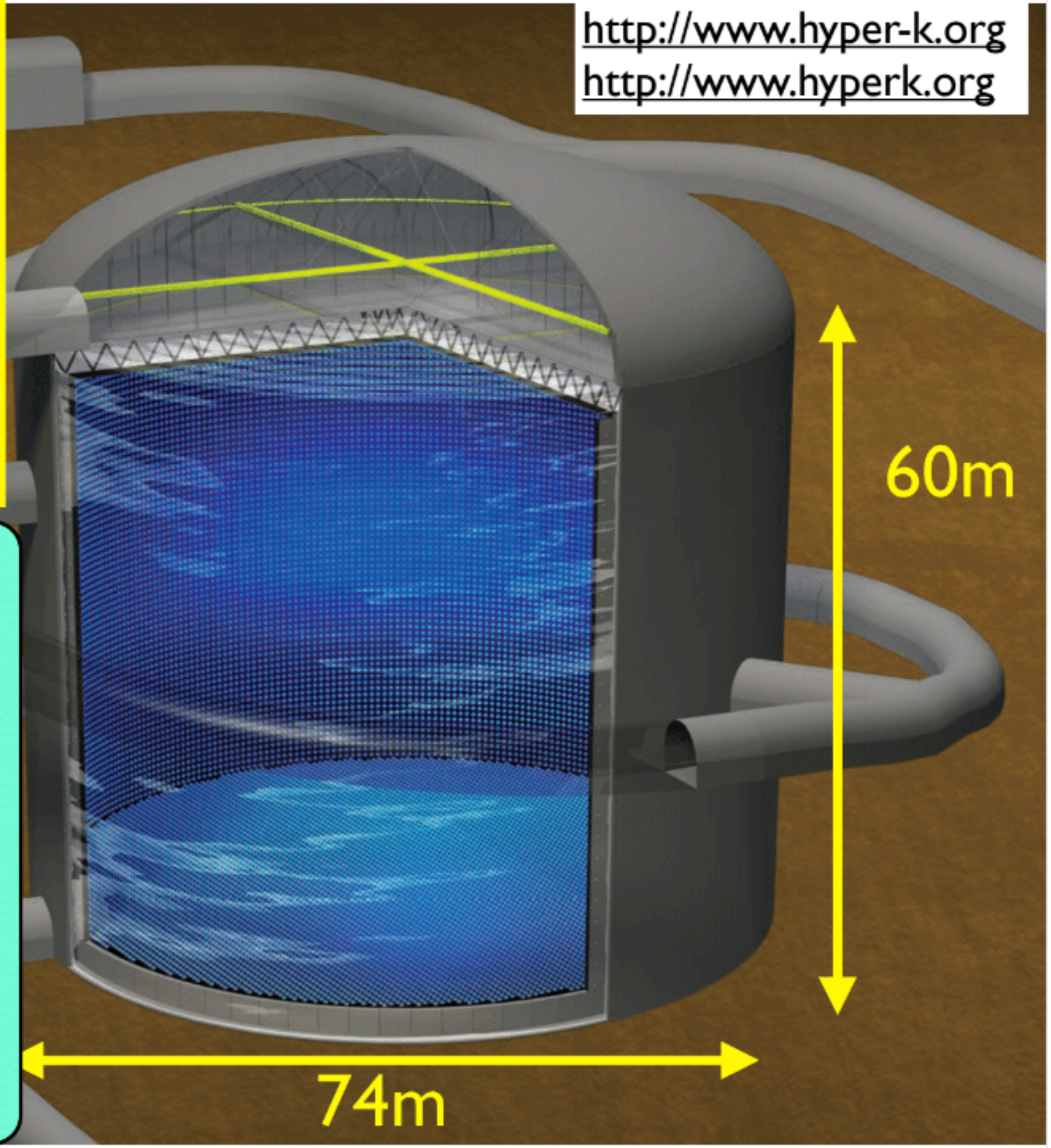


The Hyper-Kamiokande detector

HK Design Report: arXiv:1805.04163

http://www.hyper-k.org
http://www.hyperk.org

superb capabilities
for a broad area
of science,
proven feasibility

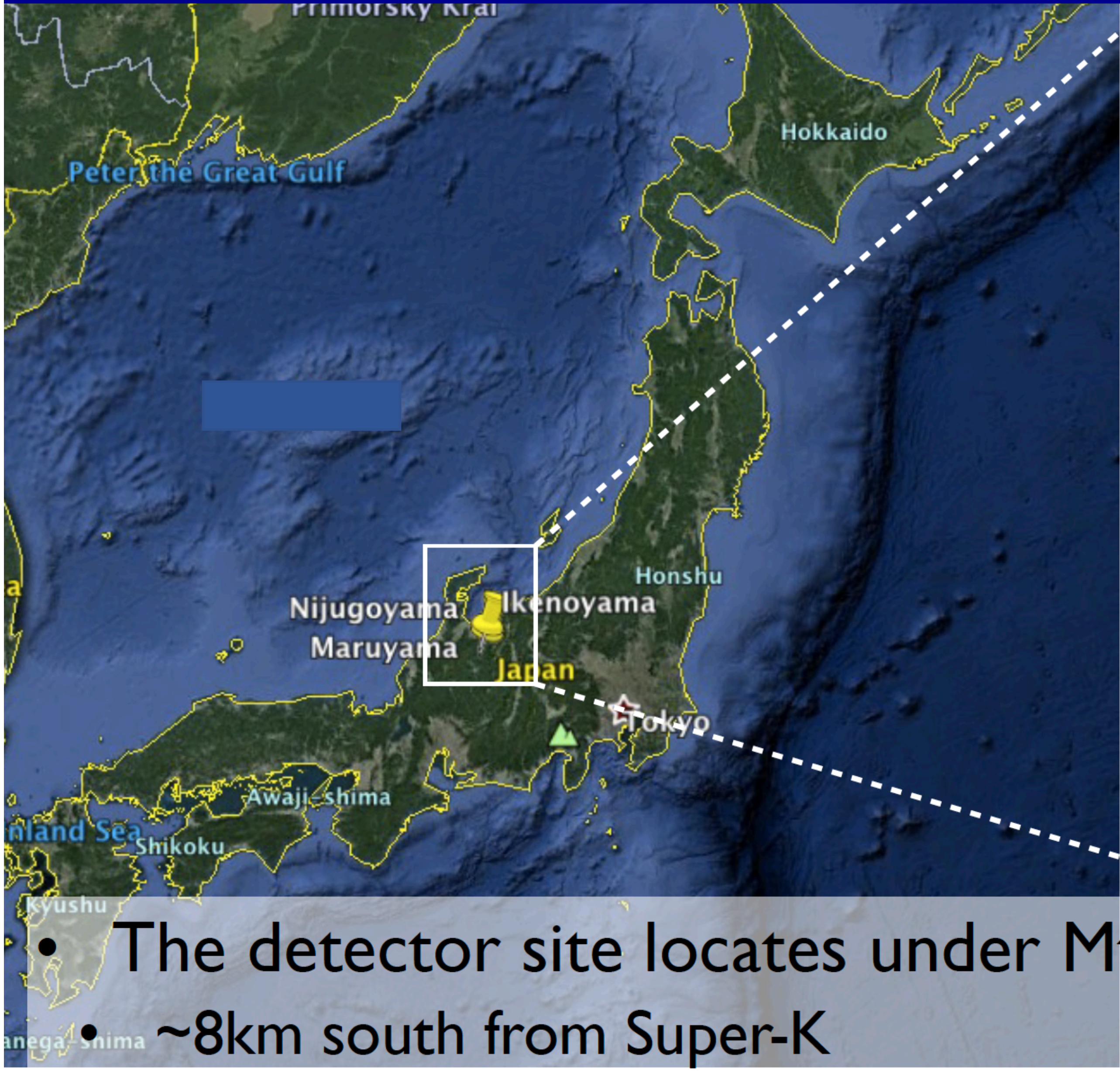


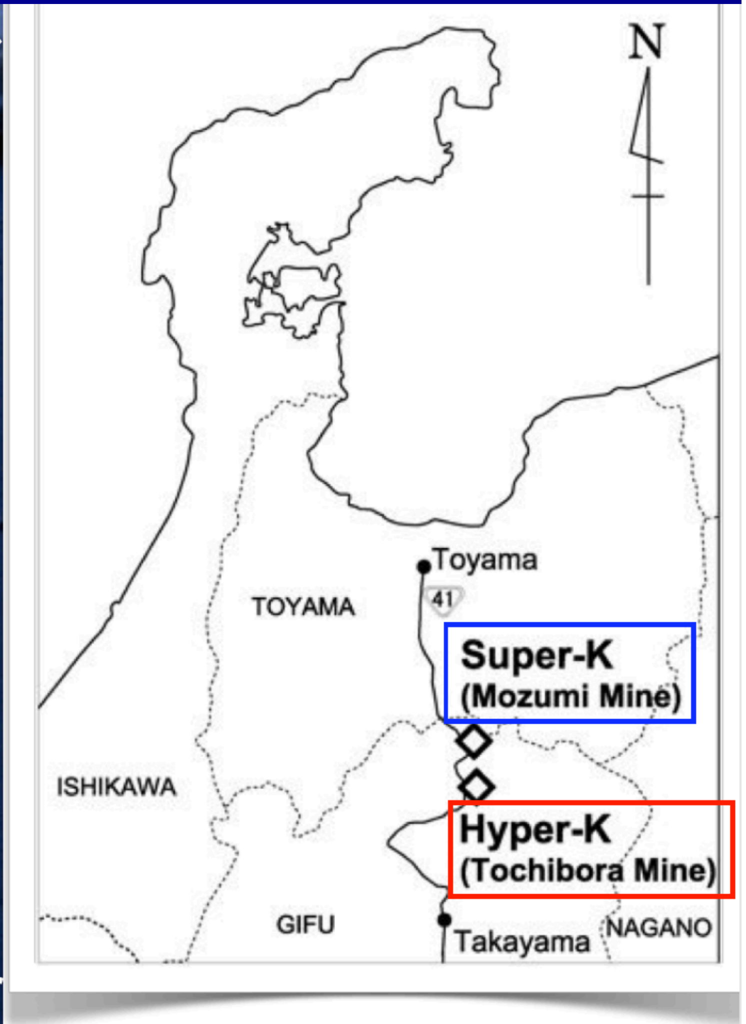
Optimized for cost and quick start
Total volume: 260kton per tank
Fiducial volume: 190kton per tank
(~×10 of Super-K per tank)

Start with one tank (funding request)
40% coverage with new sensor
×2 photon sensitivity
~40,000 50cm PMTs for inner det.
~~~6,700 20cm~~ PMTs for outer det.

~15k 3 inch PMTs for OD (cheaper, less dark rate)
~~~

Hyper-K Site





- The detector site locates under Mt. Nijugo-yama
  - ~8km south from Super-K

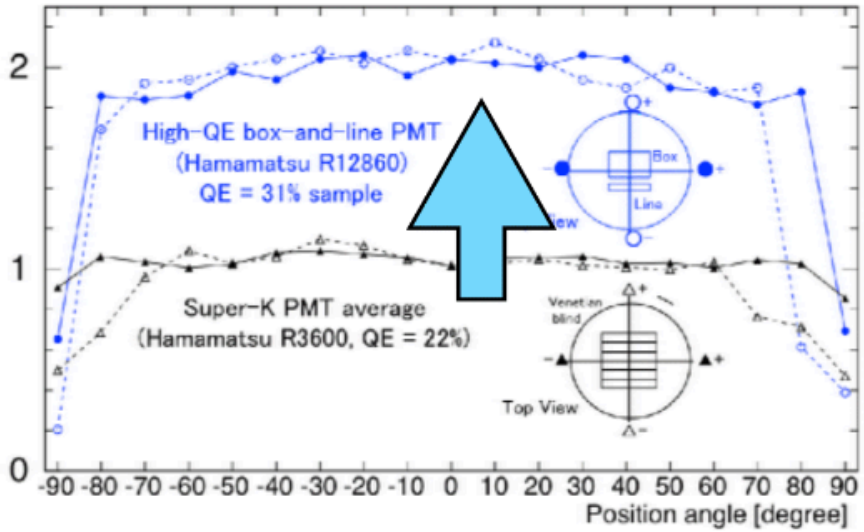
650 m overburden

- Identical baseline (295km) and off-axis angle (2.5deg) to T2K

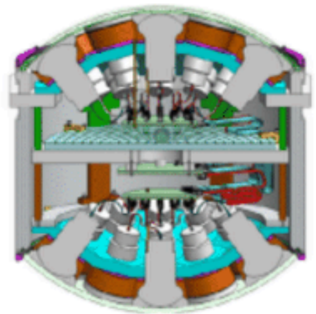
Enabling technology: new photosensors

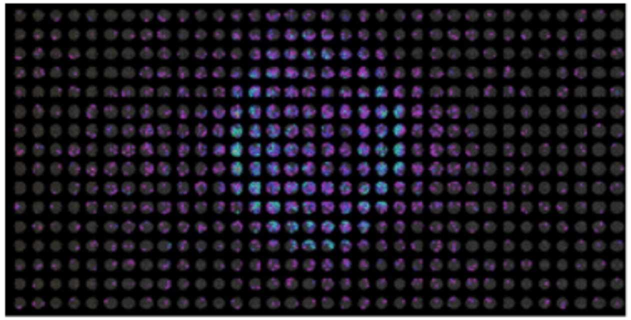
HPK R12860

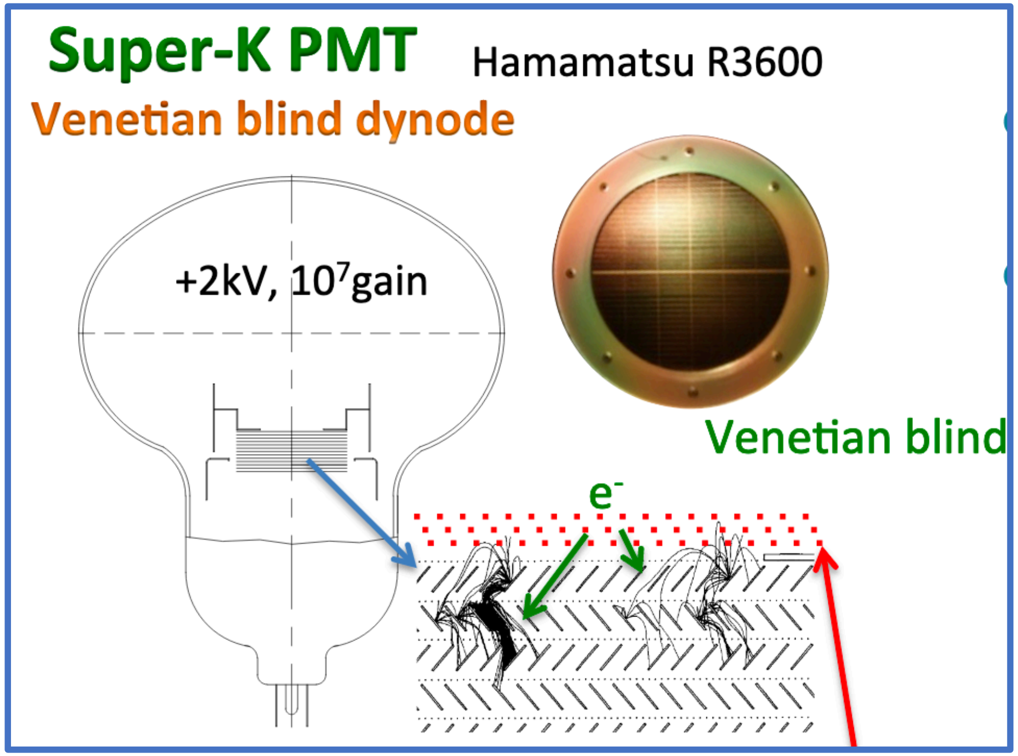
50cm

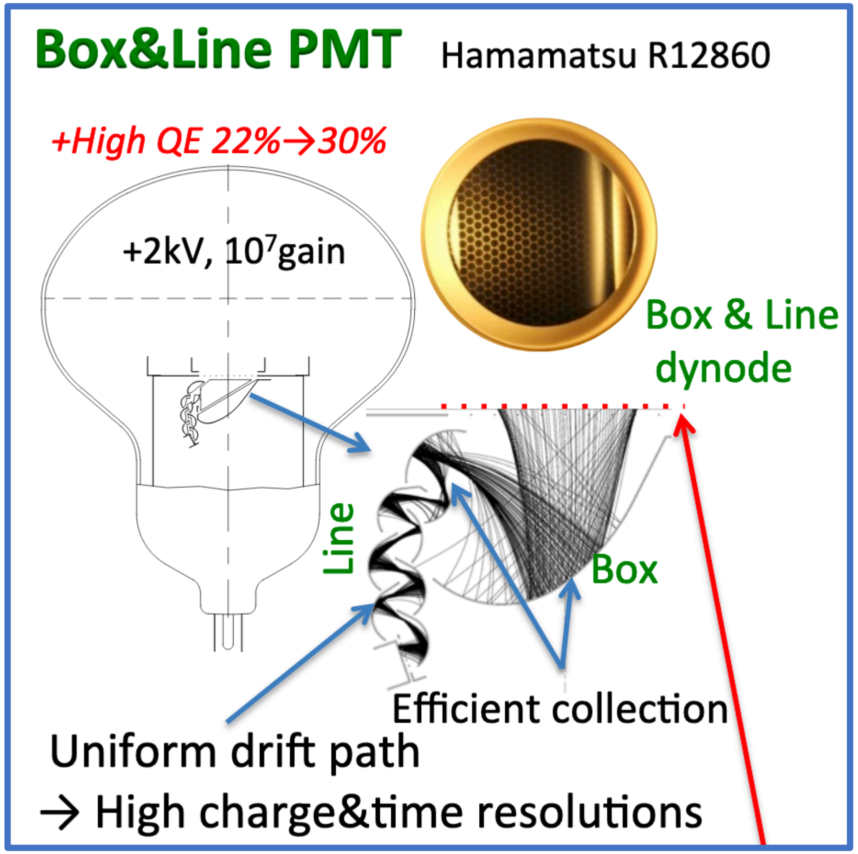


- Better performance than SK-PMT (R3600)
  - Photon detection efficiency ×2
  - Timing resolution ×2
  - Better pressure tolerance
- Intensive R&D for "multi-PMT" option by an international collaboration
  - Module of small PMTs in an enclosure









	SK (HR3600)	HK (HR12860)
Collection Efficiency	40~50%	70%
QE	22%	30%
Transit Time Spread (σ)	4.4 ns	2.2 ns
Rise Time	20 ns	10 ns
FWHM of signal	30 ns	18 ns

Status of New Photo Detectors

- Hamamatsu Box&Line PMT
  - ~140 PMTs were manufactured and installed to Super-K.
  - 5000 PMTs for JUNO, most of them arrived and waiting for waterproofing.
  - Mass production is ready for Hyper-K.
    - Final R&D to lower dark rate is ongoing.
- Hamamatsu HPD
  - 1 waterproof HPD was installed to the EGADS water tank for the proof test.
  - Need to establish a mass production technique for Hyper-K.
- NNVT MCP PMT
  - 15k PMTs for Juno, in production and waiting for waterproofing
    - Performance test and visual inspection are also ongoing near to Juno.
  - For Hyper-K, a prototype with waterproof cover and cable comes soon. Tuning for more improved high QE and lowered dark rate is ongoing.
- Incom LAPPD
  - 8-inch prototypes were realized and are being tested.
  - Need to establish mass production technique for the large number.

Light Collectors

- Cost effective solution to enhance detection efficiency

Studies on light collection for KamLAND2-Zen

Winston cone

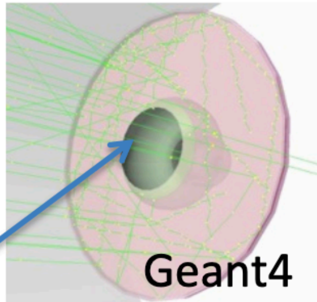
→ x1.8 enhancement

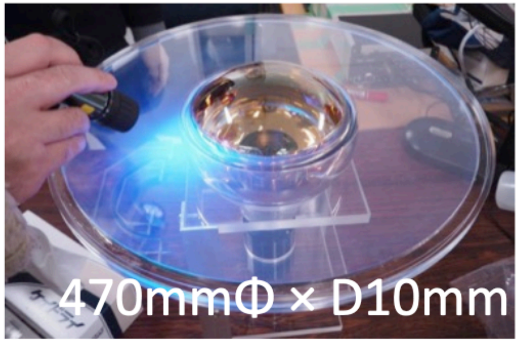
Study with simulation and measurement
Test of stability, background, etc.

Wavelength shifting plate

Polystyrene w/
POPOP for test

8” R5912 PMT





Prototype

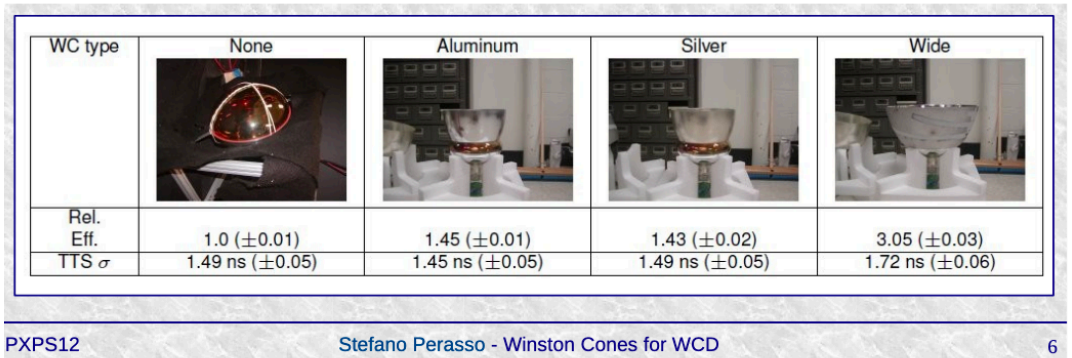
w/acrylic plate and mirror in edge for reflection

About 1.5 factor

in both measurement and simulation

Mirror optimization for WCD by S.Perasso

https://indico.fnal.gov/event/5276/material/slides/0?contribId=66

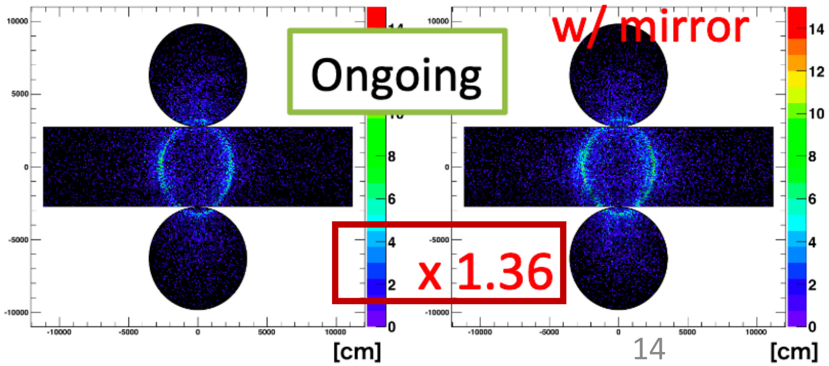


WC type	None	Aluminum	Silver	Wide
Rel. Eff.	1.0 (±0.01)	1.45 (±0.01)	1.43 (±0.02)	3.05 (±0.03)
TTS σ	1.49 ns (±0.05)	1.45 ns (±0.05)	1.49 ns (±0.05)	1.72 ns (±0.06)

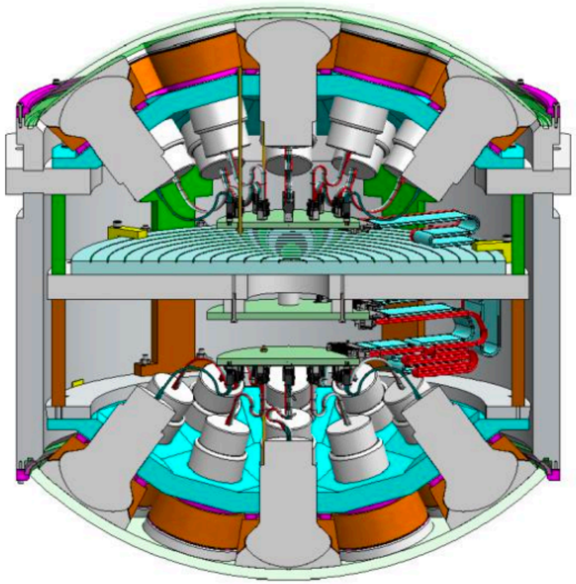
PXPS12 Stefano Perasso - Winston Cones for WCD 6

Tested best shape

Simulation study for Hyper-K



multi-PMTs



International Effort

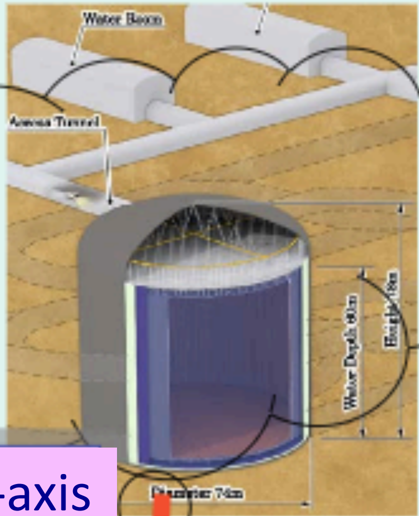
- Collection of small size (3 inch) PMTs in a single enclosure
- Adapted from KM3NET's original mPMT
- **Pro:**
  --better timing properties
  --better directionality
  --better pressure tolerance
  --better vertex reconstruction near wall
  → fiducial volume increase
- **Con:**
  larger number of channels
  → more expensive and power consumption

Hyper-K Two Detectors

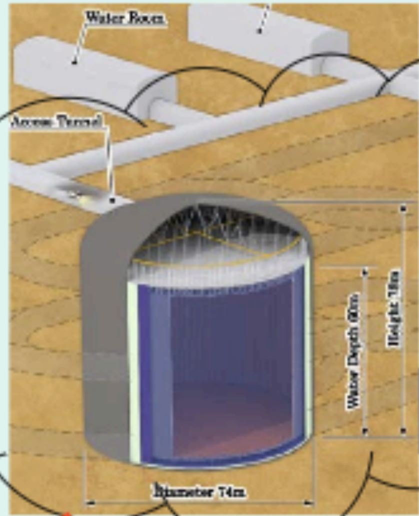
T2HKK

KNO

Korean
Neutrino
Observatory



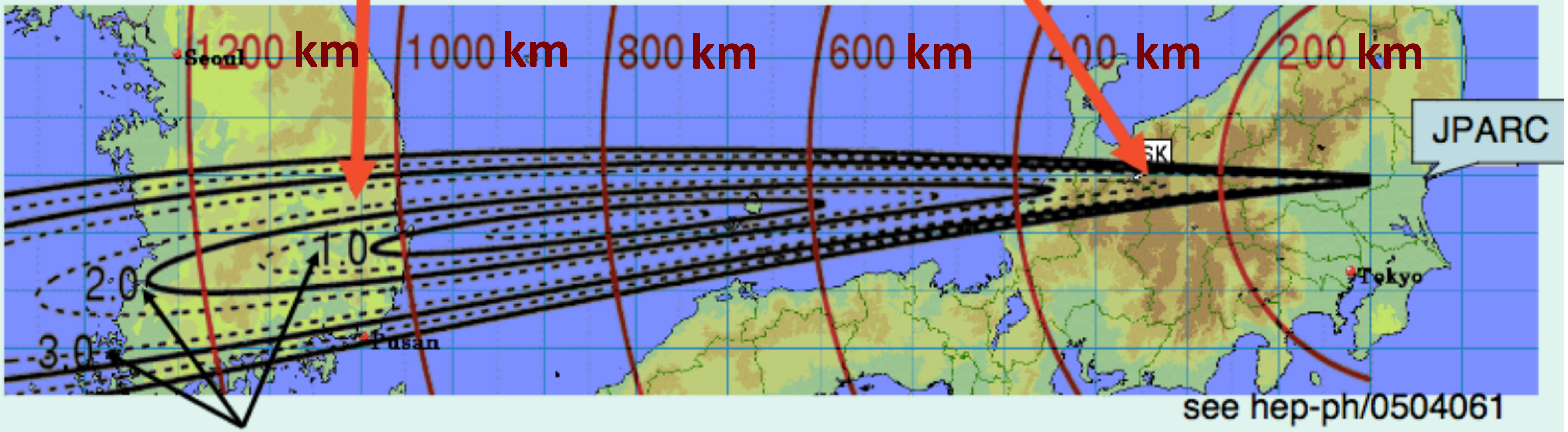
1~3 deg. off-axis



Hyper-K

2.5 deg. off axis

The J-PARC ν beam comes to Korea.



see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

E. Witten

"Why don't you bring one of the 2 tanks to Korea ?"
@EPP2010

T2HKK Inauguration
July 10th 2016, London

Brief History of T2HKK/KNO (I)

- 2005/2006/2007: a large Cherenkov detector in Korea using J-PARC neutrino beam (T2KK) was suggested.
  → 3 joint workshops supported by KOSEF and JSPS.

- 2015: staged construction of two HK detectors at Kamioka
  2 X 260 kton → 1 X 260 kton (2017)

- March 20, 2016: initial discussion on T2HKK at Fermilab

- July 10, 2016: official kick-off meeting in London
  → T2HKK proposal was accepted in Hyper-K.
  T2HKK working group (WG10) was formed.

- Sept. 2, 2016: 1st domestic T2HKK workshop at SNU

Brief History of T2HKK/KNO (II)

- ❑ Nov.19, 2016: T2HKK white paper release to arXiv:1611.06118
  → published in PTEP in Mar. 2018.

- ❑ Nov. 21-22 2016: 1st International T2HKK workshop at SNU

- ❑ Nov. 2017: 2nd Domestic Workshop for T2HKK in KNU

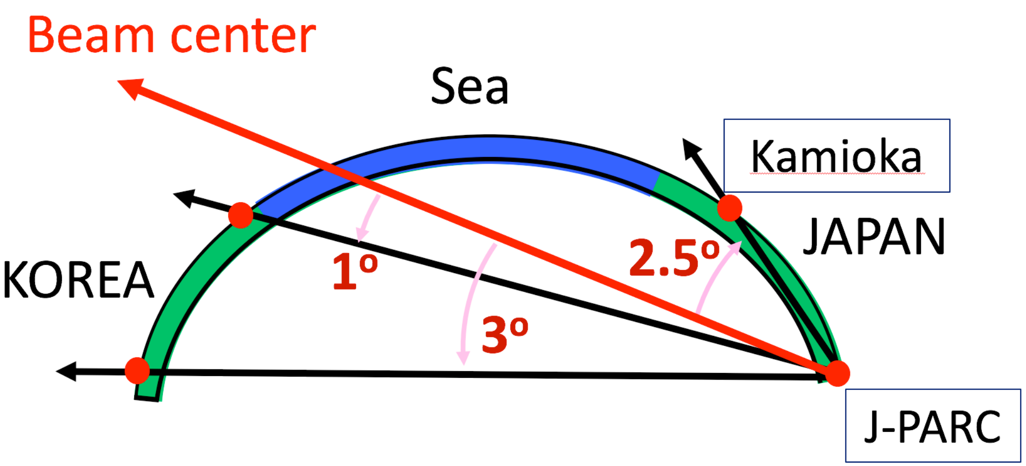
6. July 2018: Hyper-K Satellite Meeting during ICHEP, Seoul.

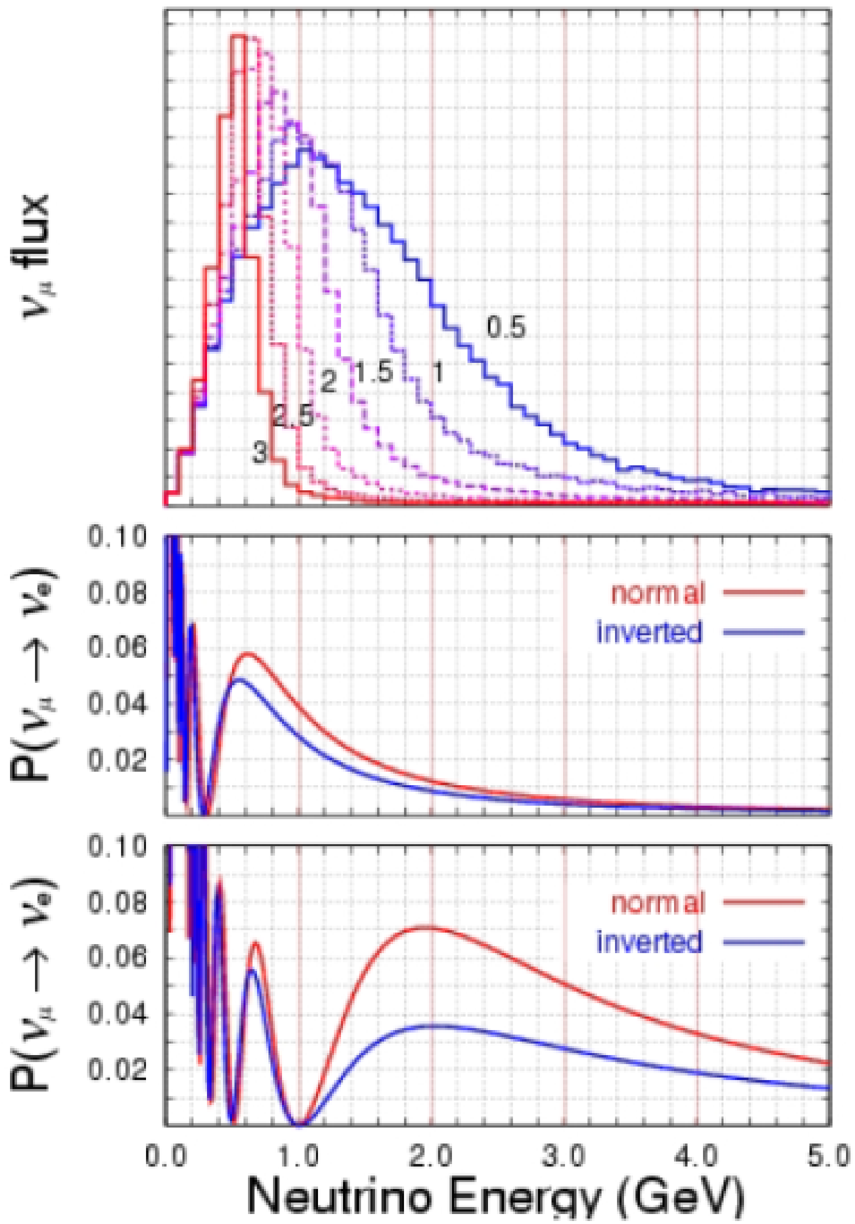
   https://indico.snu.ac.kr/indico/event/47/overview

- ❑ Nov. 2018: 3rd Domestic Workshop for T2HKK in KNU

- ❑ Aug 2019: Hyper-K Satellite Meeting during NuFACT at KNU

Neutrino Oscillations in Kamioka & Korea





← Profile of off-axis beams

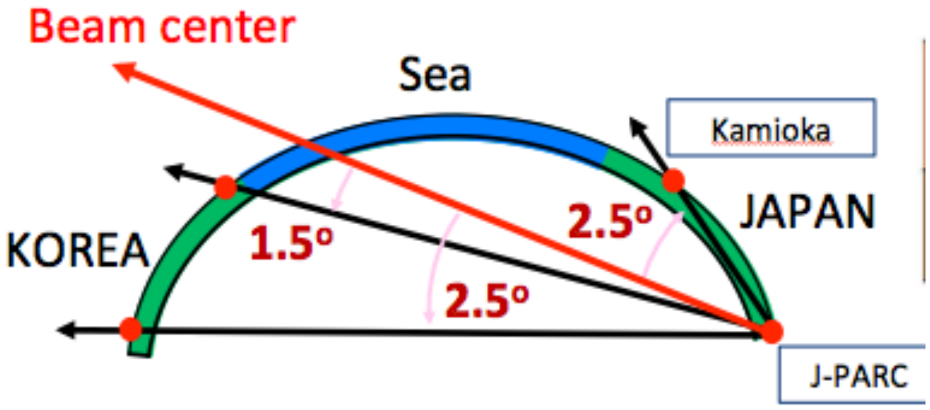
← $P(\nu_\mu \to \nu_e)$ at SK/HK (Japan)

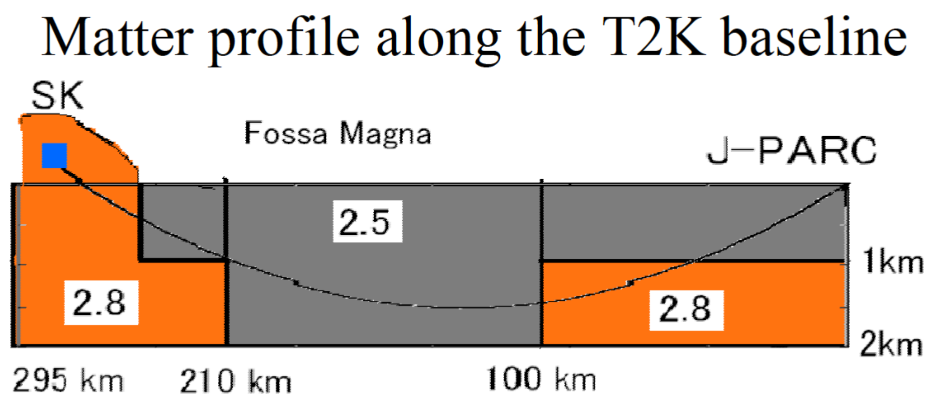
(L = 295 km)

← $P(\nu_\mu \to \nu_e)$ at Korea

(L=1000km)

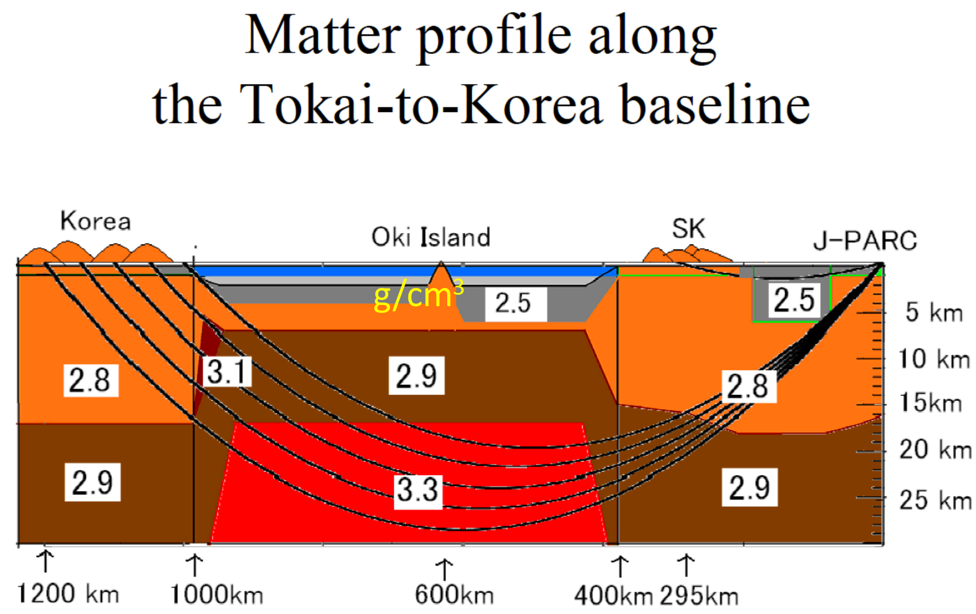
Off-axis Beam and Matter Density





Matter term:

$$r_A = 2\sqrt{2}G_F N_e E_\nu / \Delta m^2_{31}$$

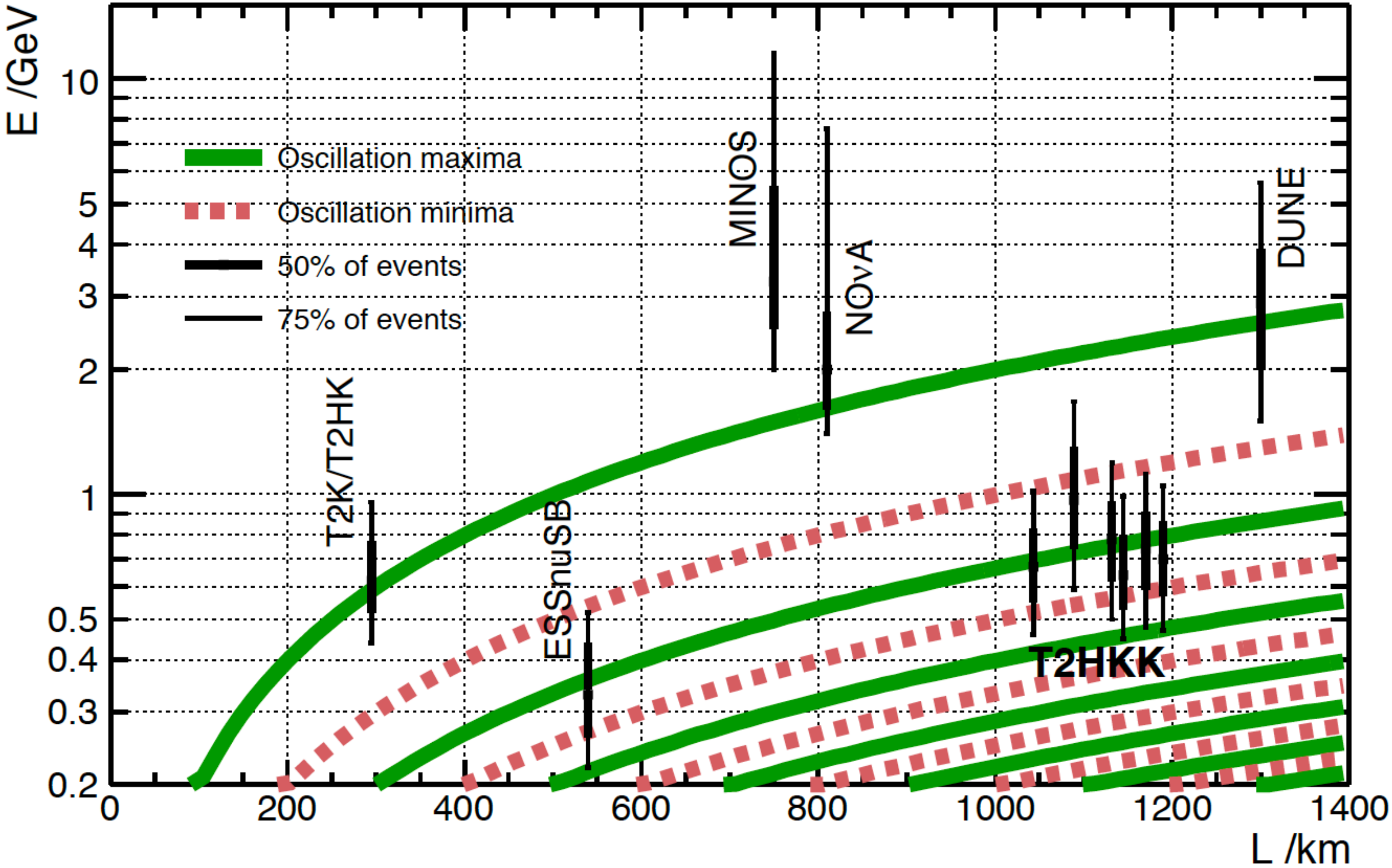


More matter effects

→ better MO determination

- Longer baseline
- Higher matter density
- Higher neutrino energy

Energy vs. Baseline



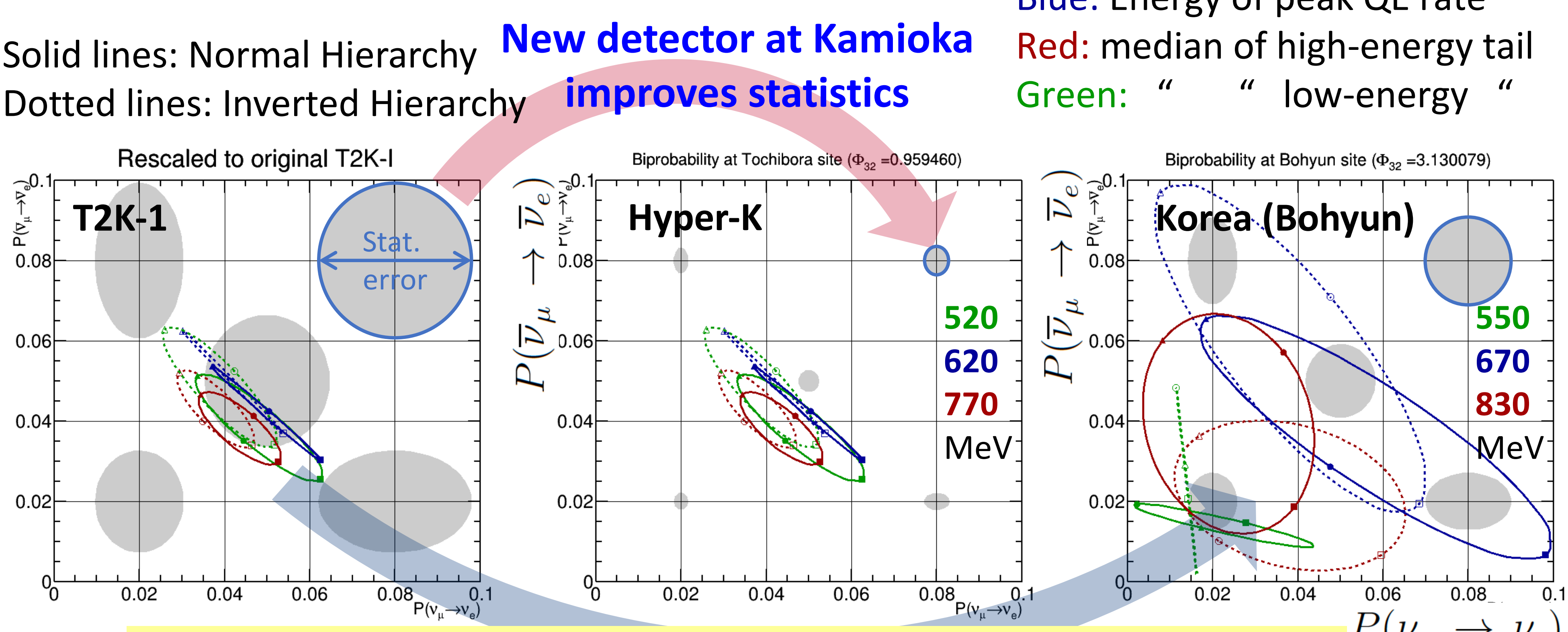
Unique benefits of a Korean Detector

Biprobablitiy plots often used to compare experiments. (e.g. T2K vs NOνA). Extend these to multiple energies, to gain understanding of 2nd maxima measurement.

Larger ellipses mean less sensitivity to systematic errors.
Shape differences unpick degeneracies with other parameters. (e.g. θ_{23})

Solid lines: Normal Hierarchy
Dotted lines: Inverted Hierarchy

Blue: Energy of peak QE rate
Red: median of high-energy tail
Green: " " low-energy "



Detector in Korea measures parameters in a very different way

Benefits of the 2nd Detector in Korea

T2HKK = **T**okai to(**2**) **HK** to **K**orea

The following physics sensitivities are improved by locating the 2nd detector to Korea

- Neutrino mass ordering determination
- Leptonic CP violation measurement

← **1st&2nd oscillation maxima**

- Non-standard neutrino interaction

← **Higher ν energy**
Longer baseline
Higher matter density

- Solar/SRN/ν geo physics sensitivities

← **Deeper site: 650 vs. 1000 m**

Important Questions

expected to be answered by Hyper-K/T2HKK.

- Leptonic CPV ?
- ν mass ordering determination ?
- NSI ?
- Supernova burst/relic neutrinos ?
- Proton decay ?
- Dark matter ?
- etc.

In this talk

Why Leptonic CPV ?

1. Which flavor symmetry model ?

Understanding pattern of ν mixing

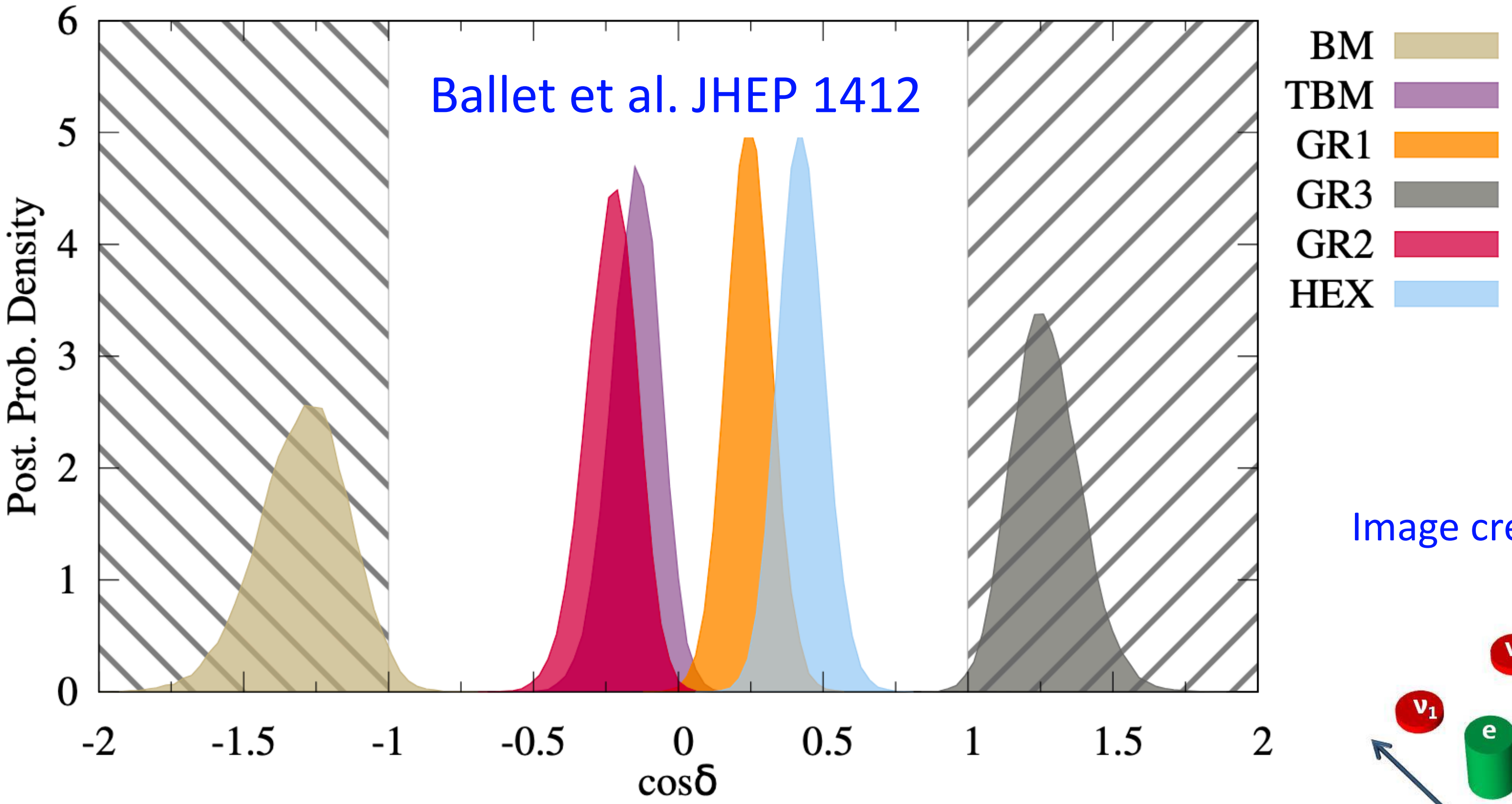
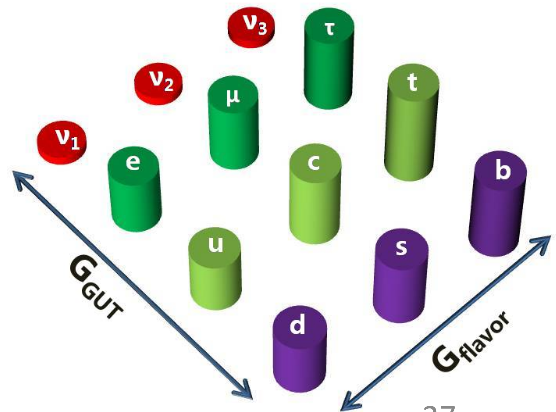


Image credit: T. Ohlsson @KTH



Why CPV in Lepton Sector?

- CP structure in quark sector is well known.
  → Small CPV in quark sector (< 10^{-7} %)
  can not explain baryon asymmetry of the universe.

- However, **leptogenesis** may explain baryon asymmetry, provided with large CPV in lepton sector.

- There is **hint** of maximal CPV in lepton sector.
  (~ 2sigma @T2K, NOvA)

$$
\begin{array}{ccccc}
 & & \mathrm{CP} & & \\
 & \nu_\mu \to \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \to \bar{\nu}_e & \\
\mathrm{T} & \Updownarrow & & \Updownarrow & \mathrm{T} \\
 & \nu_e \to \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \to \bar{\nu}_\mu & \\
 & & \mathrm{CP} & &
\end{array}
$$

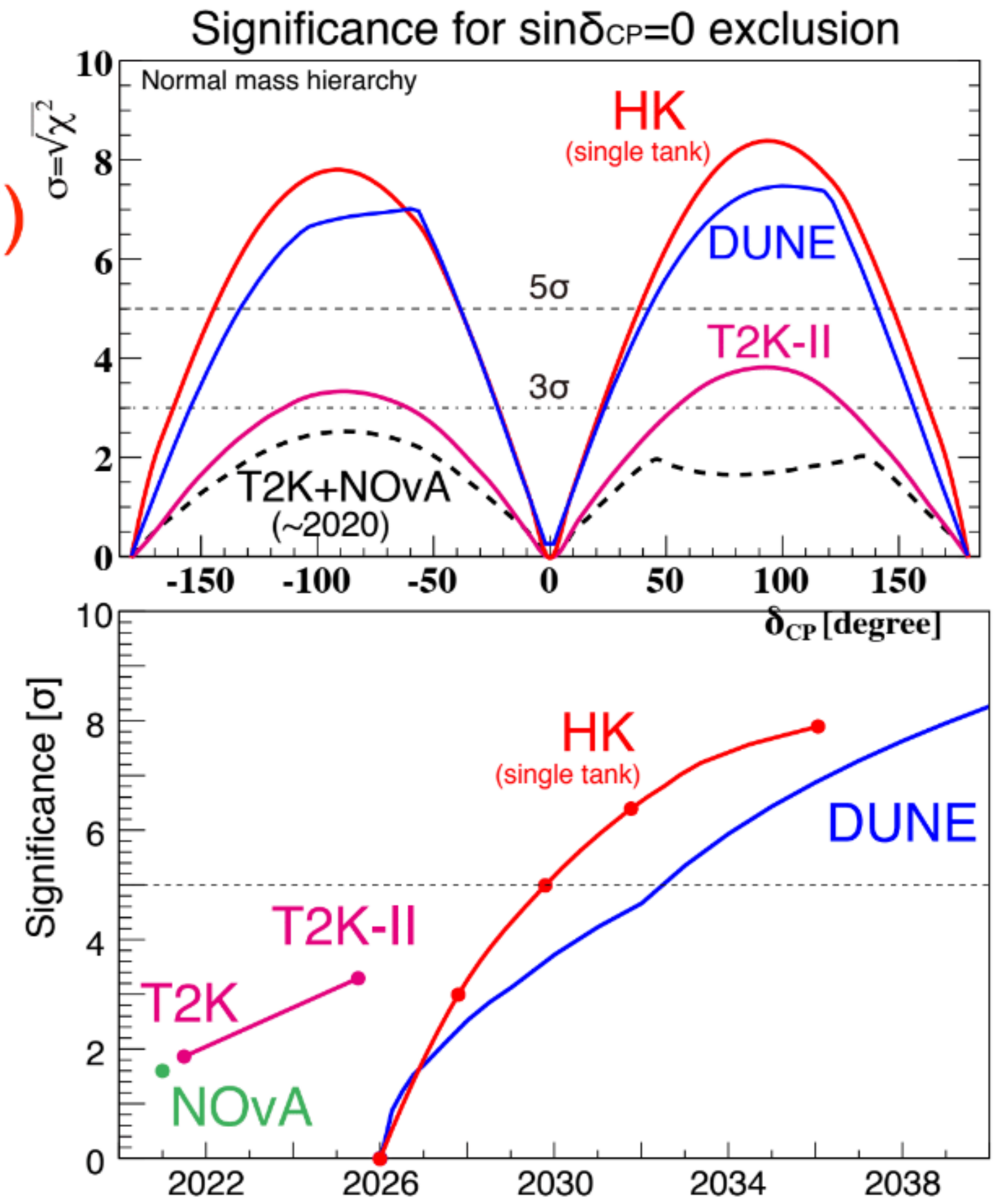
$$
P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}
\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)
$$

Expected sensitivity: CP violation

- Exclusion of $\sin\delta_{CP}=0$
  - ~8σ(6σ) for δ=±90°(±45°)
  - >3σ(>5σ) significance for ~76%(58%) of δ_{CP} space
- δ_{CP} resolution:
  - 22° for δ_{CP}=±90°
  - 7° for δ_{CP}=0°or 180°

Seamless program of Japan-based experiments for study of CP-violation

T2K→T2K-II→HK



δ_{CP} & MO Sensitivity Studies

**** Simulation parameters ****

- 2.7×10^{22} POT with $\nu : \bar{\nu}$ = 1 : 3 operation ratio

  → 10 years of operation with 1.3 MW beam

- 187 kton fiducial volume (compared to 22.5 kton for SK)
- Baseline to Korea is 1100 km
- Off-axis beam: 1.5°, 2.0°, 2.5°
- Oscillation parameters: →

$$|\Delta m^2_{32}| = 2.5\times10^{-3}\ \text{eV}$$
$$\sin^2\theta_{23} = 0.5$$
$$\sin^2 2\theta_{13} = 0.085$$
$$\Delta m^2_{21} = 7.53\times10^{-5}\ \text{eV}$$
$$\sin^2\theta_{12} = 0.304$$
$$\delta_{cp} = 0, \pi/2, \pi, 3\pi/2$$

◆ Note: Relatively simple systematic uncertainty model is used.
More realistic systematic uncertainty implementation is needed.

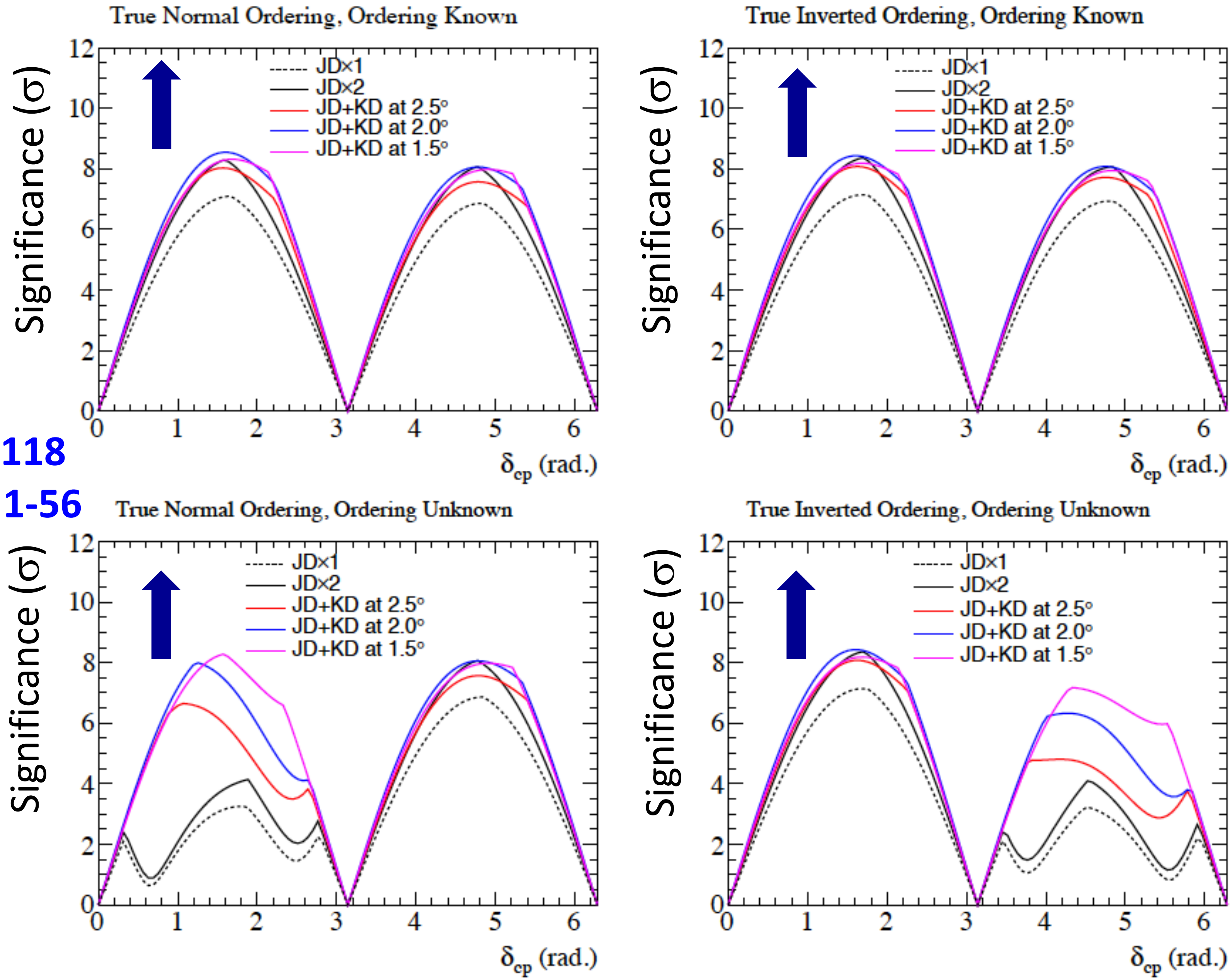
δ_{CP} Sensitivities

Known MO

Unknown MO

arXiv:1611.06118

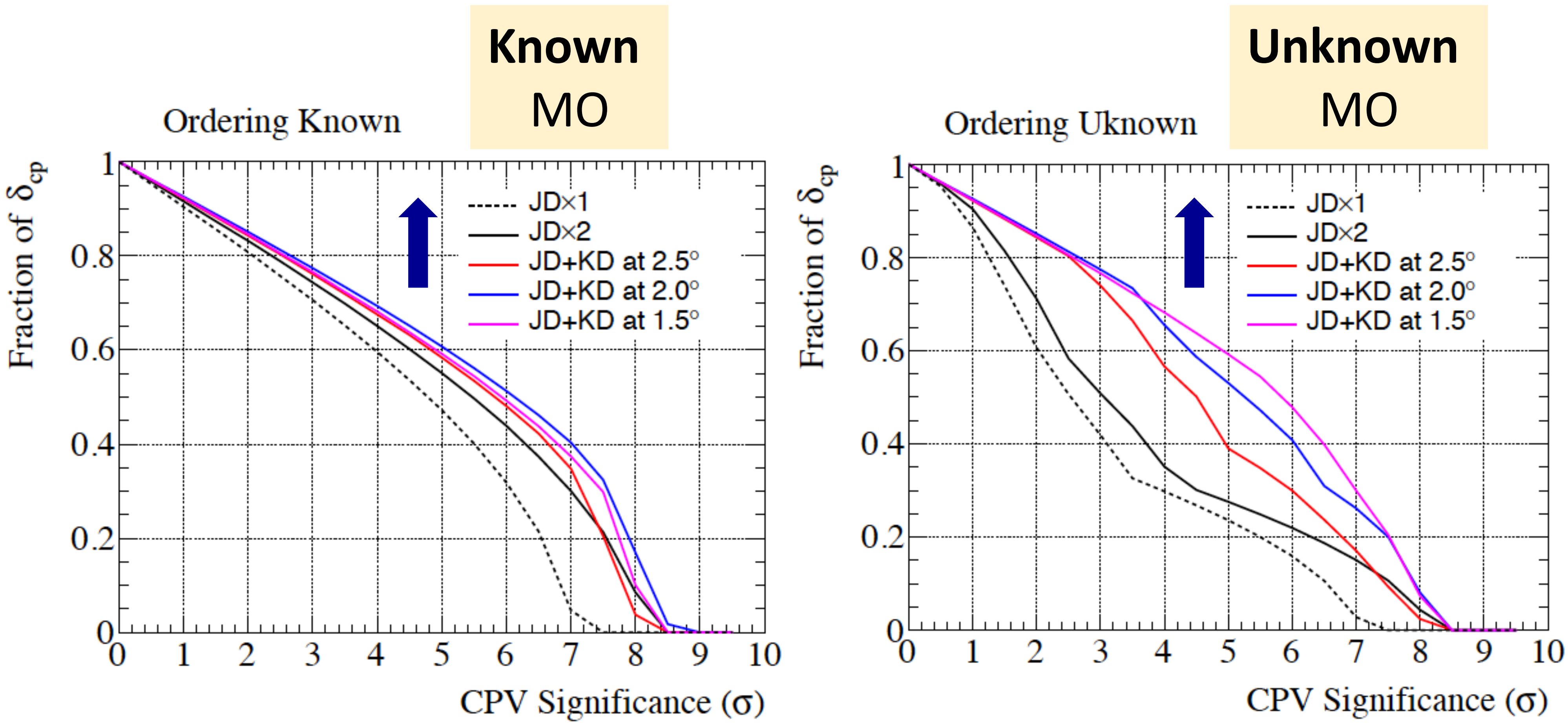
PTEP 2018, 6, 1-56



T2HKK has best sensitivity to CP phase (even) at the presence of NSI.

→ Danny Marfatia @ICHEP 2018
arXiv:1612.01443

Fraction of δ_{CP}

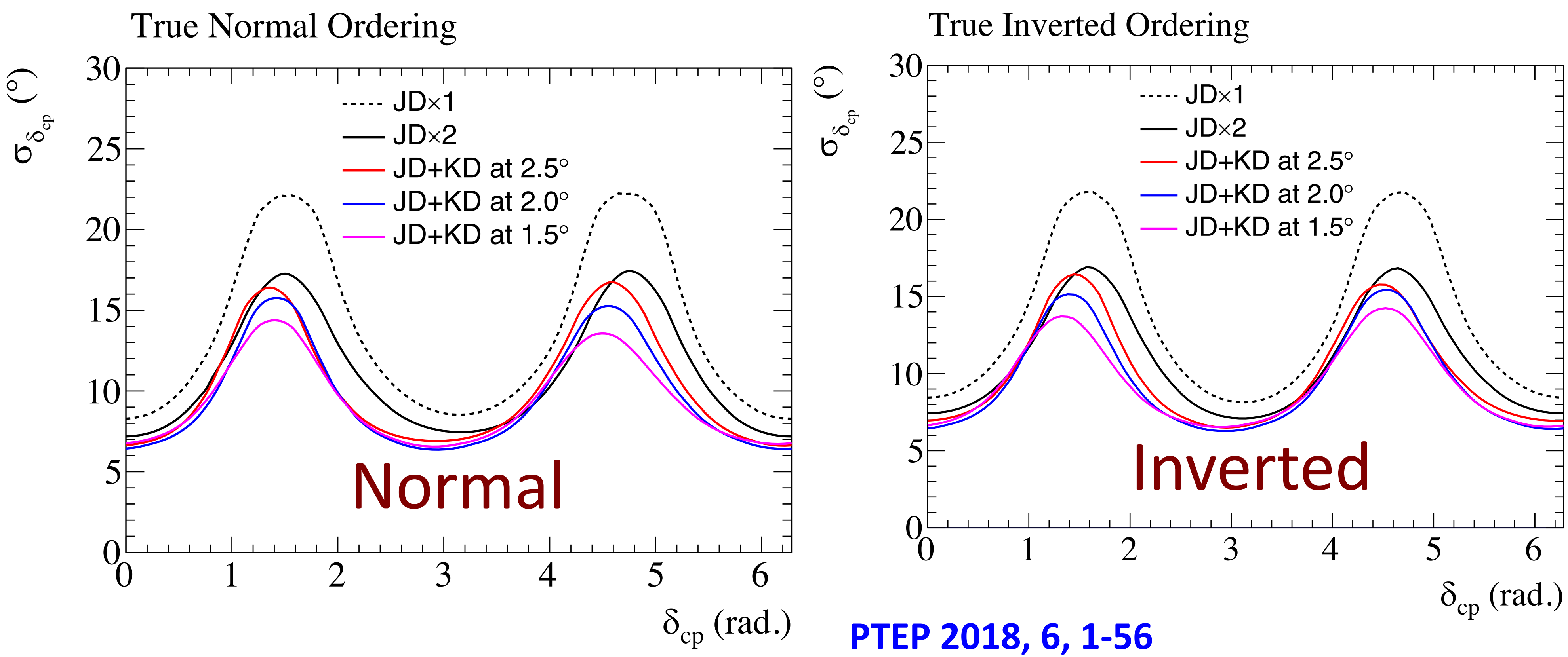


arXiv:1611.06118
PTEP 2018, 6, 1-56

Note: LBL sensitivity study was also independently done using GLoBES in PRD 96,033003 (2017).

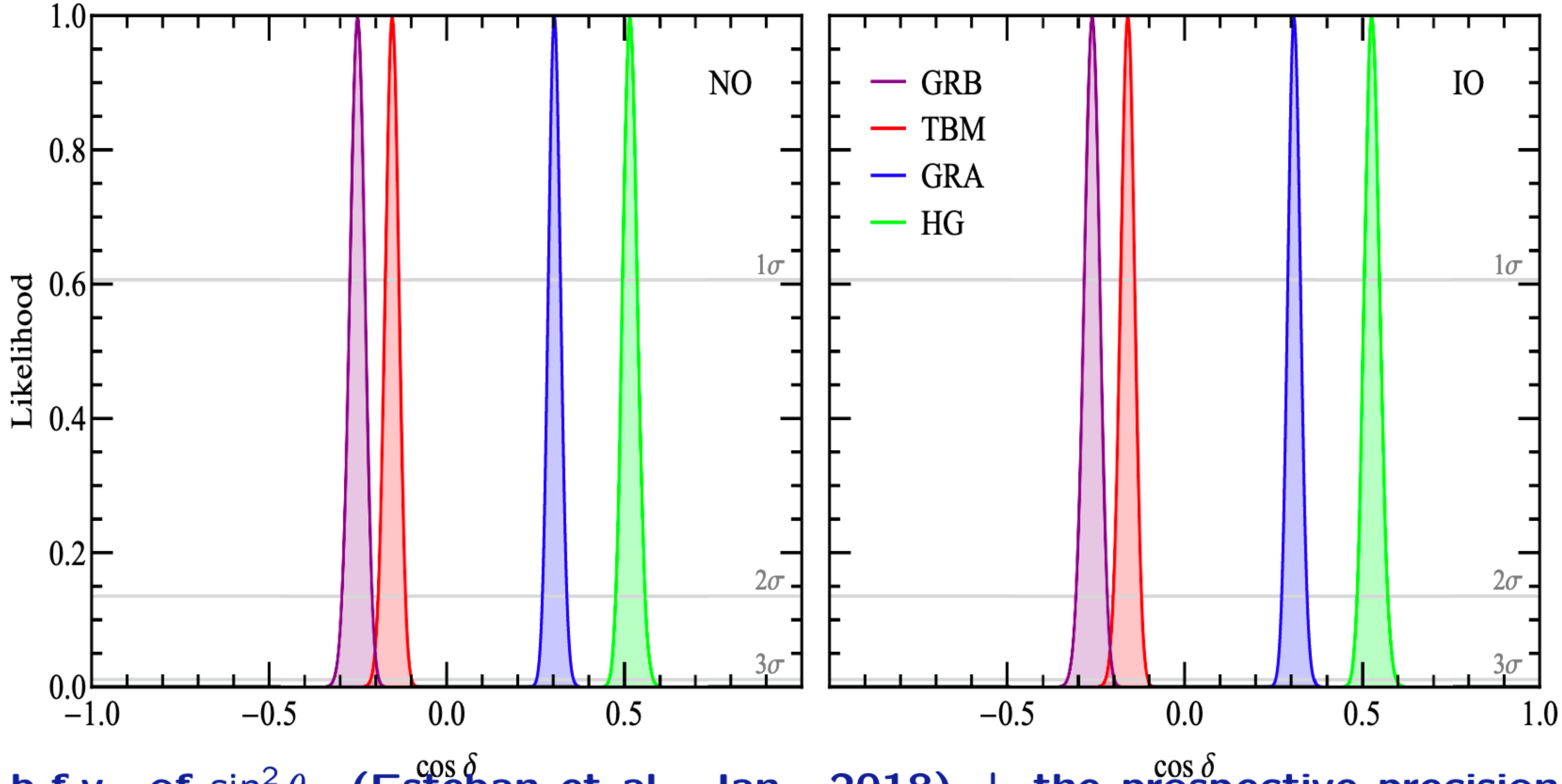
δ_{CP} Precision Sensitivities

→ Very important for flavor symmetry model of neutrino mixing
S. Petcov in ICHEP 2018



PTEP 2018, 6, 1-56

At maximum CP violation: JD+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
JD x 2 : $\sigma(\delta_{CP})$ ~ 17 degree
JD x 1 : $\sigma(\delta_{CP})$ ~ 22 degree



b.f.v. of $\sin^2\theta_{ij}$ (Esteban et al., Jan., 2018) + the prospective precision used.

F. Capozzi et al. 2018 (arXiv:1804.09678)

4.4% → $\delta(\sin^2\theta_{12}) = 0.7\%$ **(JUNO),**

3.7(IO)-3.8(NO)% → $\delta(\sin^2\theta_{13}) = 3\%$ **(Daya Bay),**

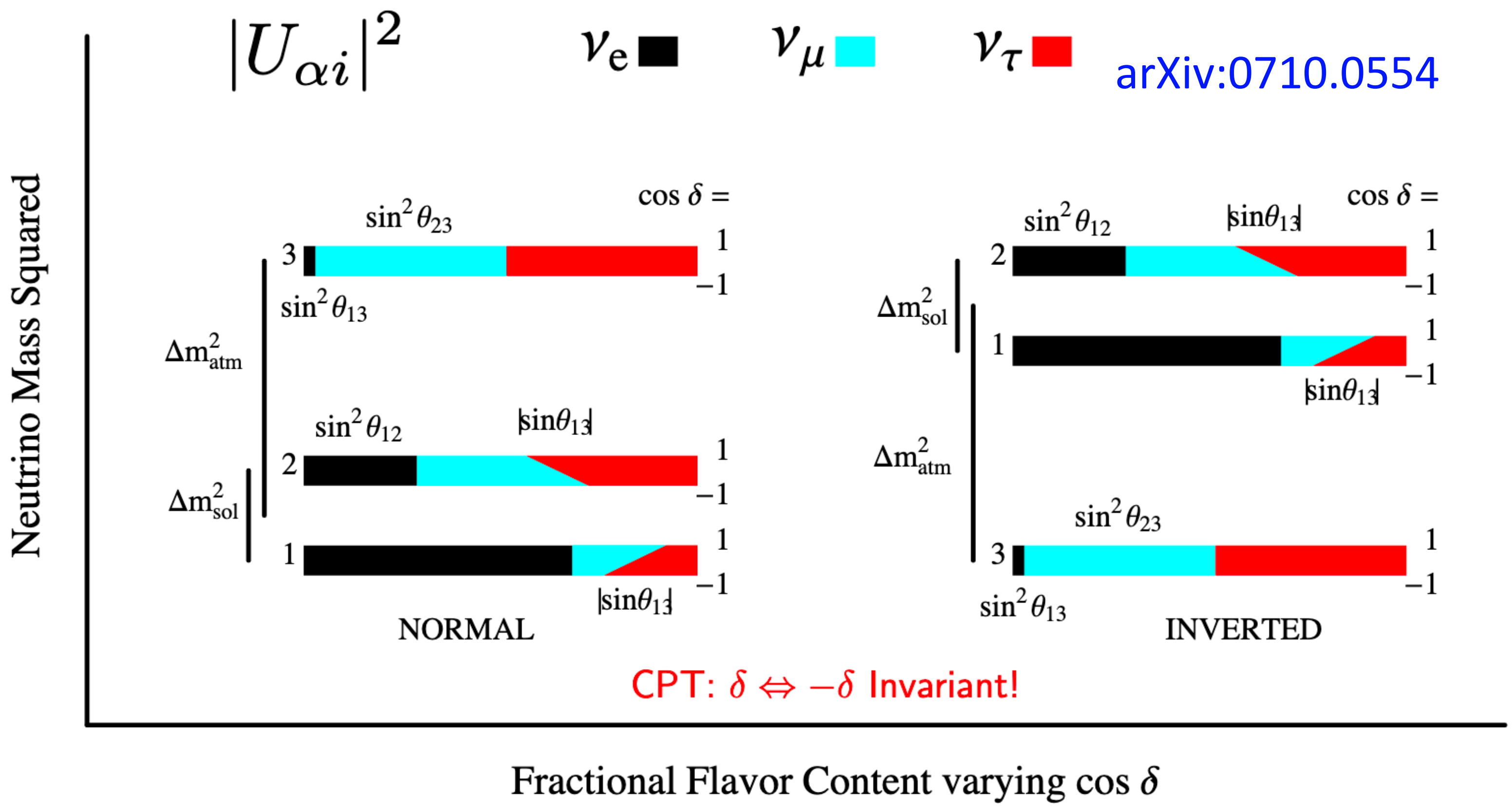
4.8(IO)-5.2(NO)% → $\delta(\sin^2\theta_{23}) = 3\%$ **(T2HK, DUNE; T2K+NOνA(?)).**

25^{O}(IO)-37^{O}(NO) → $\boxed{\delta(\delta) = 10^\circ \text{ (THKK?)}}$

Prospective (useful/requested) precision:

S. Petcov talk @ICHEP2018

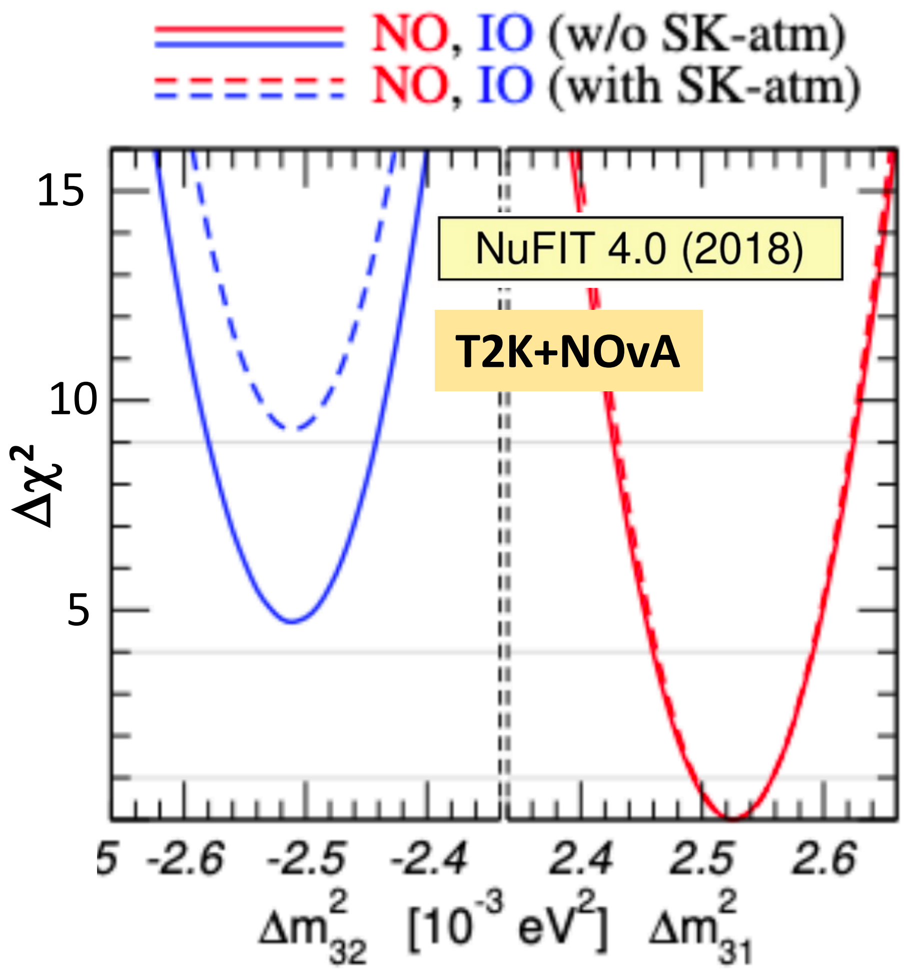
Why ν Mass Ordering (MO) ?

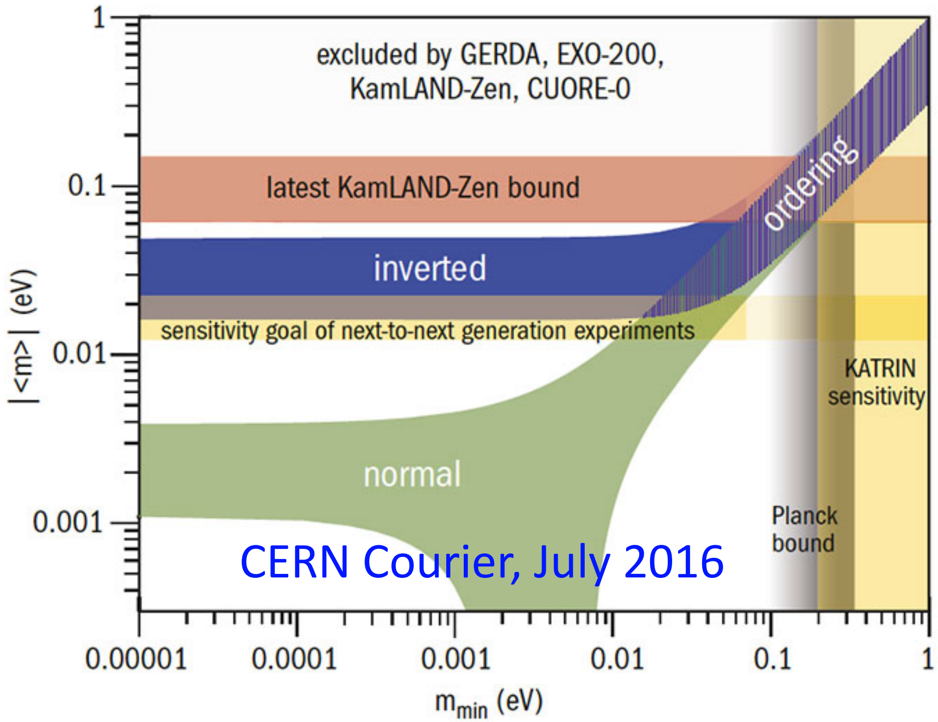


1. Important input to CPV measurement

2. Important input to flavor models

Current Status of ν MO





** Cosmological measurement (indirect / independent) favors normal ordering 3 times more from sum of ν mass

- Current best fit: normal ordering at **3.4 σ** from global fit

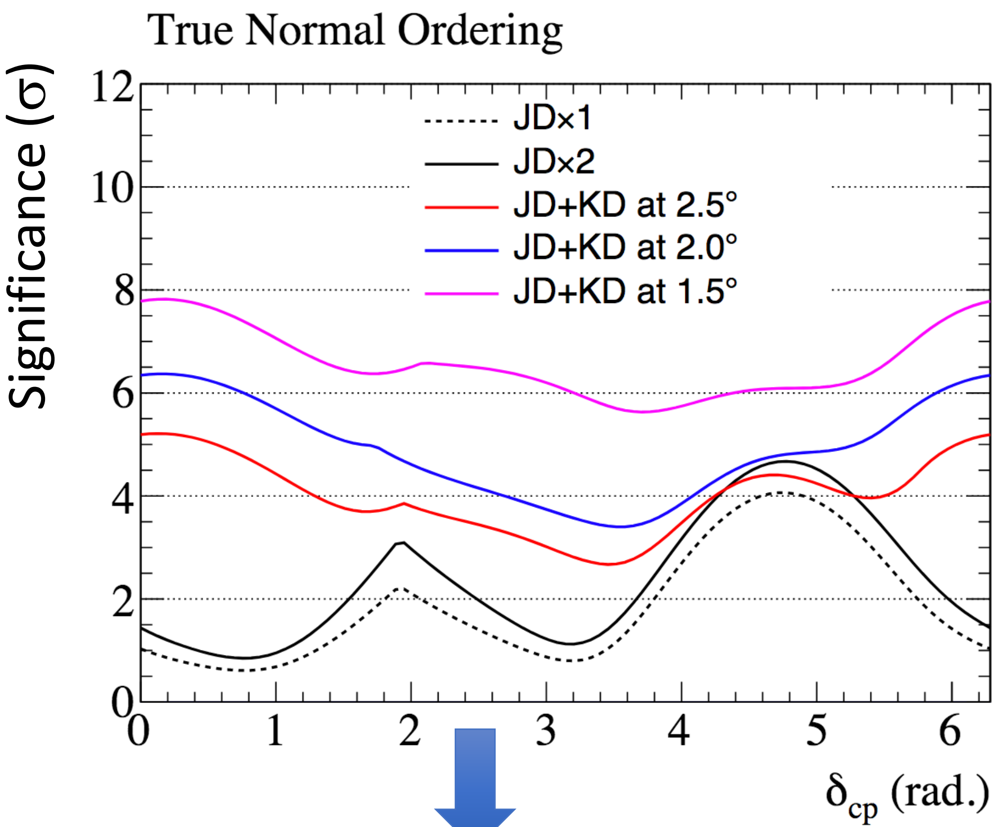
Front. Astron. Space Sci., 09 October 2018

(T2K, NOvA) + (SK) + (DB, RENO, DC)

Mass Ordering Sensitivities (Beam ν)

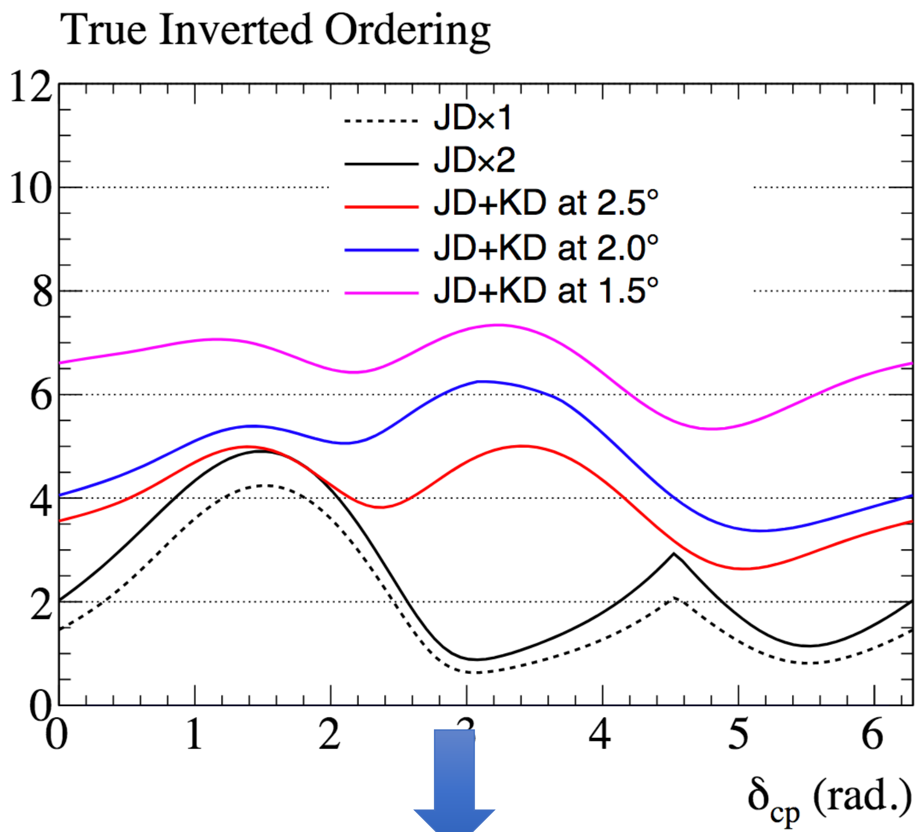
PTEP 2018,6, 1-56

Normal



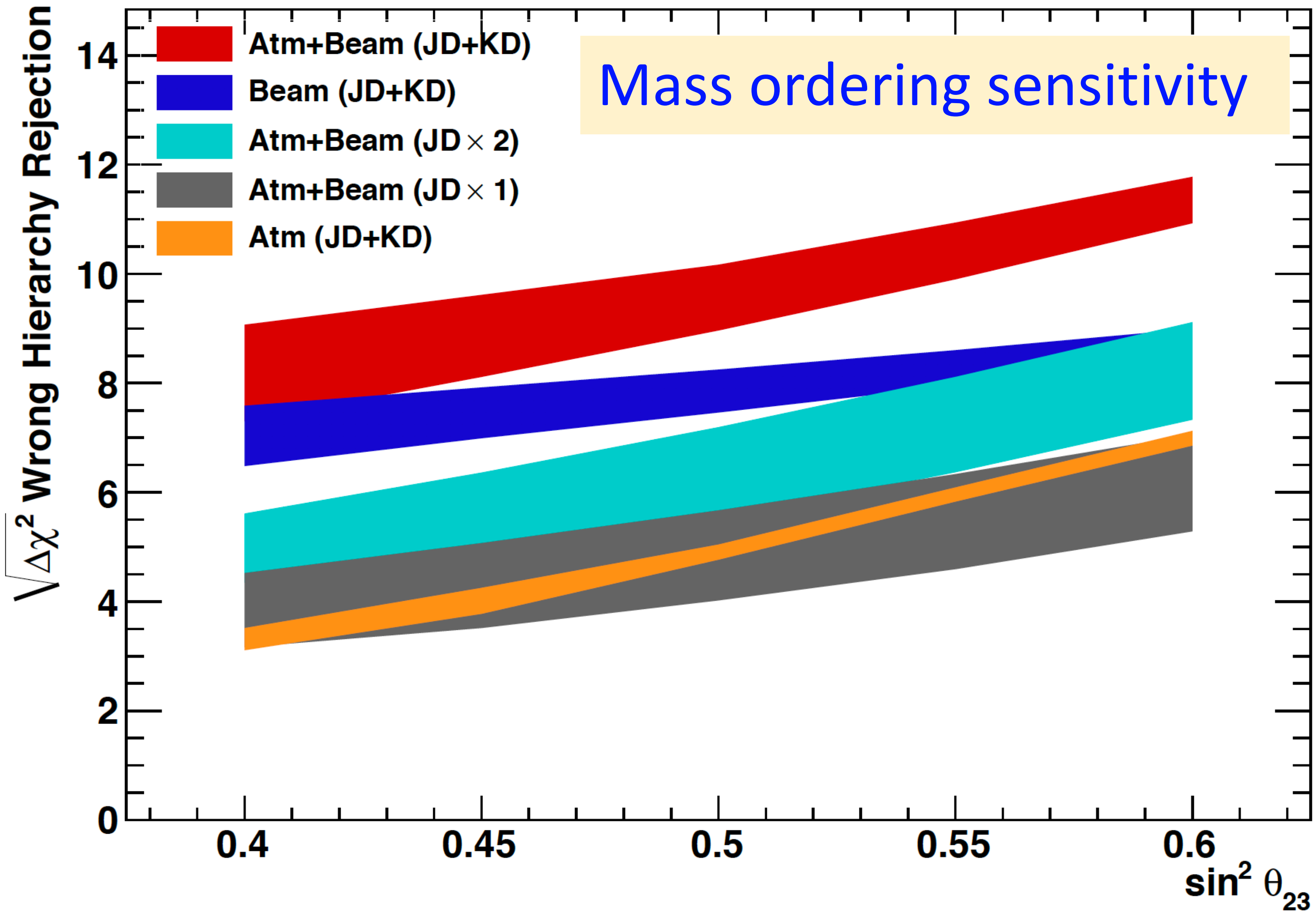
JD+KD 1.5°: 6 ~ 8 σ for all δ_{CP}
JD x2 : 1 ~ 4.5 σ for all δ_{CP}
(< 3 σ for most cases)

Inverted



JD+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}
JD x2 : 1 ~ 5 σ for all δ_{CP}
(< 3 σ for most cases)

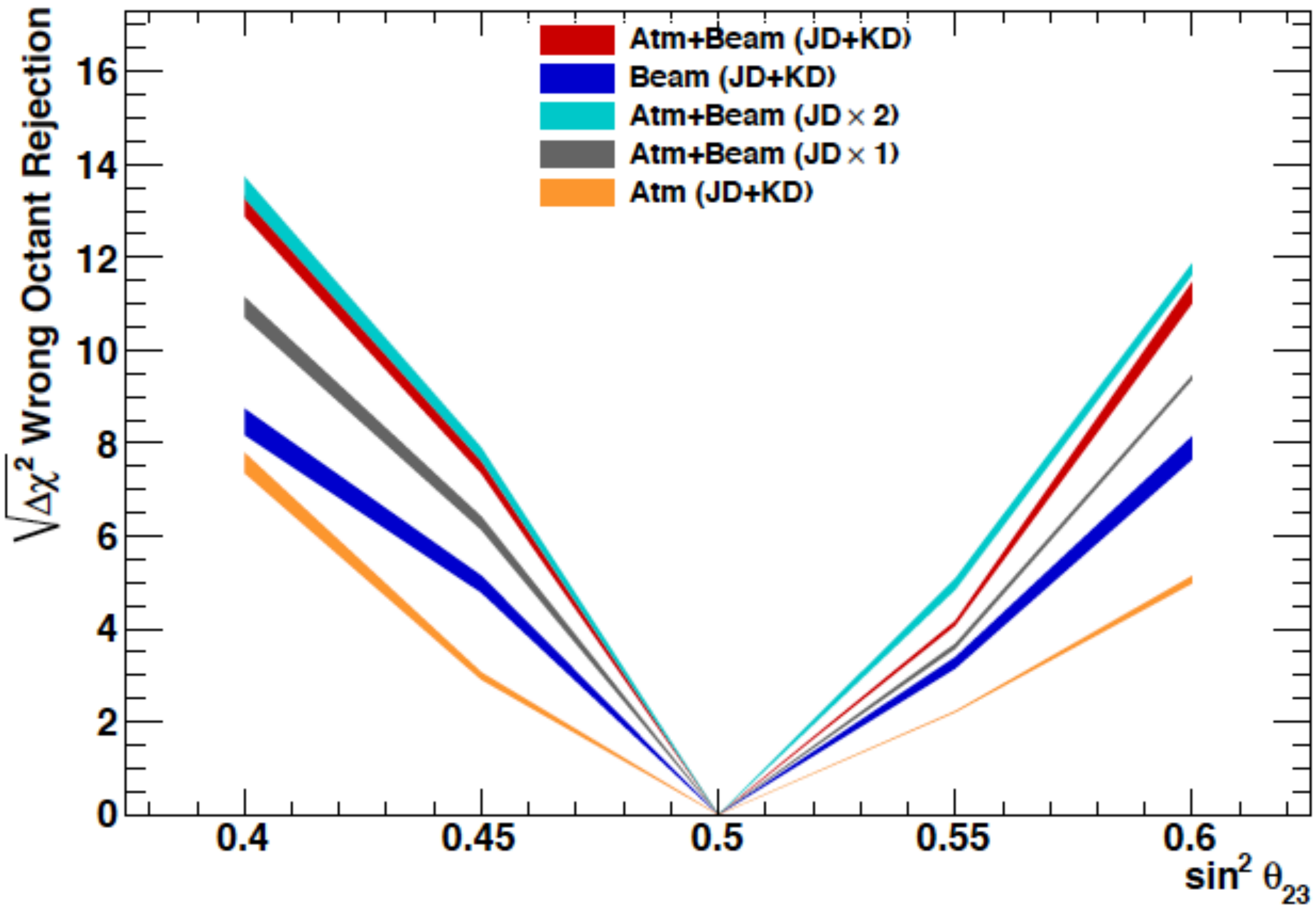
Beam + Atm. ν Data



→ Best way to determine ν mass ordering among [[ν oscillation, 0νββ, cosmology]]

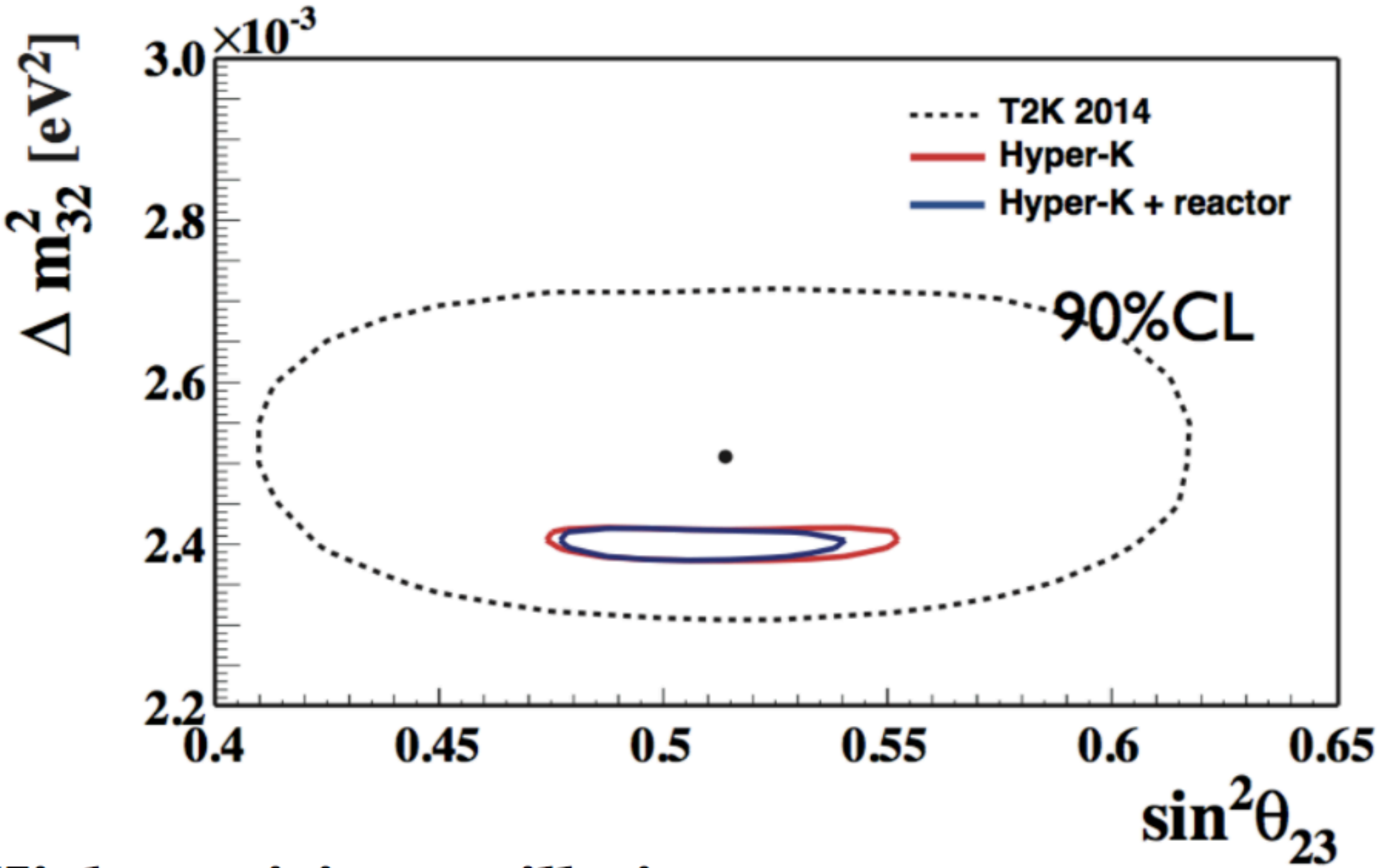
Octant Sensitivity: Beam + Atm.

θ_{23} octant sensitivity → Important for MO & CPV measurements



Atmospheric Parameter Sensitivity

Neutrino oscillation parameters



High precision oscillation parameter measurement:

1.3% $\delta(\sin^2\theta_{23}) \sim 0.006$ (for $\sin^2\theta_{23}=0.45$)

3% $\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}=0.50$)

$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\mathrm{eV}^2$

~0.6%

15

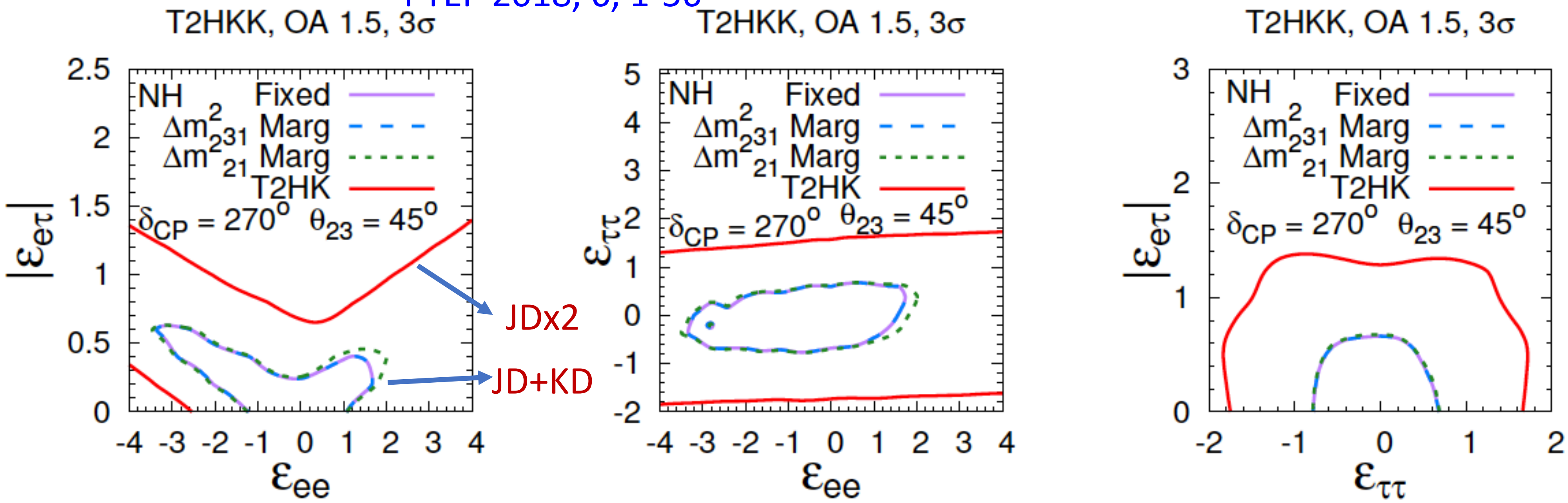
Non-standard ν Interaction Sensitivity

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{pmatrix}U^\dagger + V\right]$$

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$A \equiv 2\sqrt{2}G_F N_e E,$$

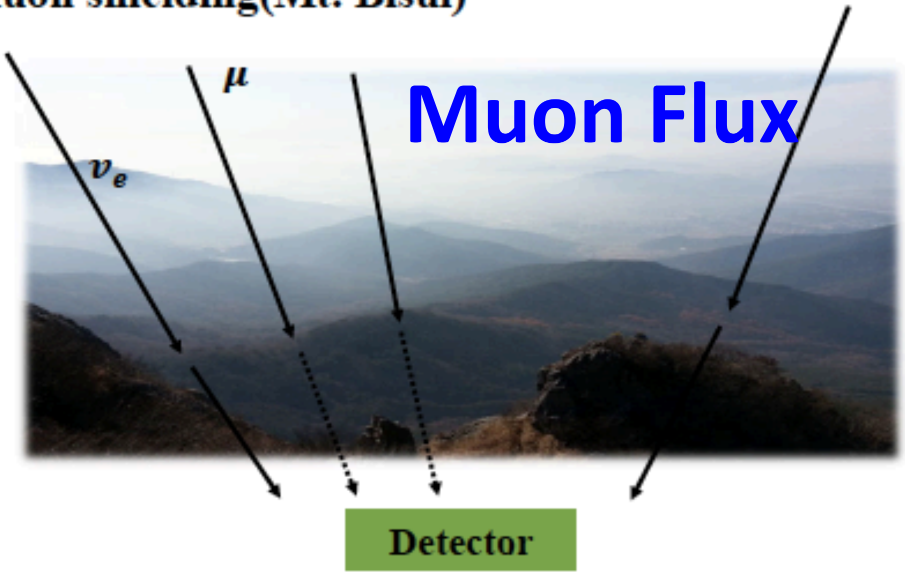
arXiv:1611.06118
PTEP 2018, 6, 1-56



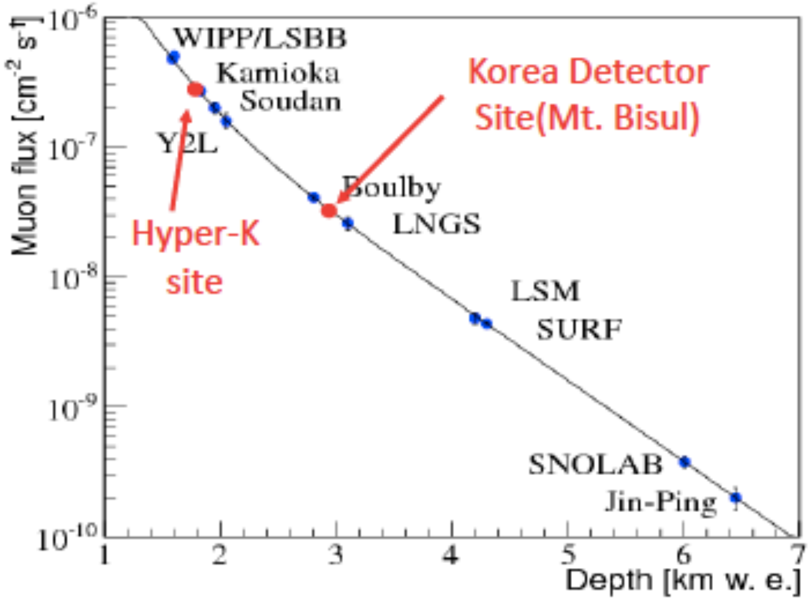
D. Marfatia@ICHEP2018: arXiv:1612.01443

"T2HKK has the best sensitivity to CP phase (even) in the presence of NSI."

Muon shielding(Mt. Bisul)

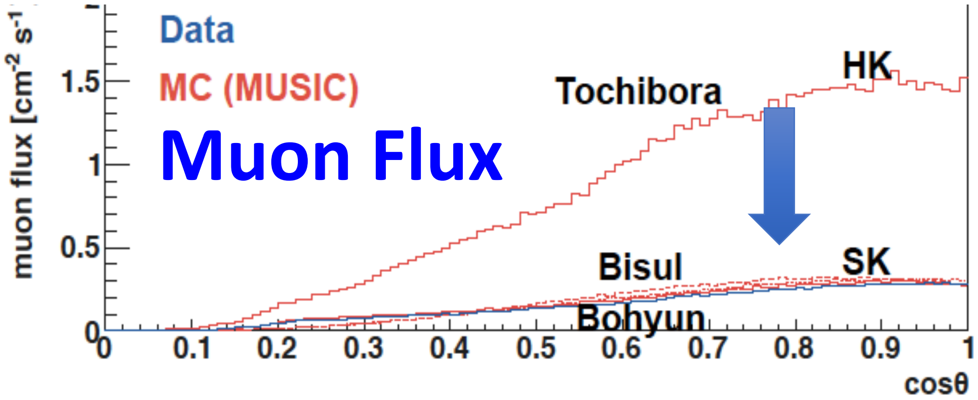


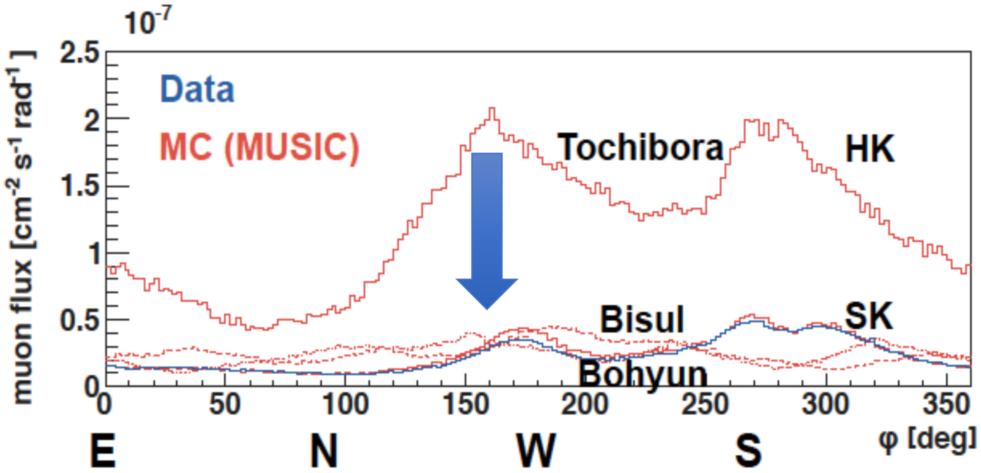
Due to the detector being located deep underground,
The background level is decreased



Muon flux to each laboratory

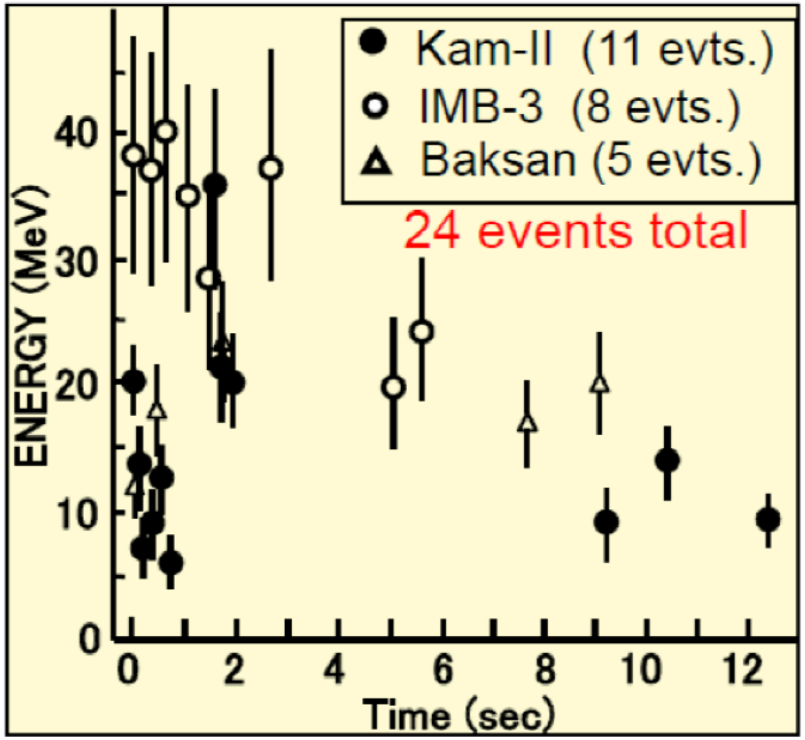
Detector site (overburden)	Φ (10^{-7} cm^{-2}s^{-1})	$\overline{E}_\mu$ (GeV)
Mt. Bisul (820 m)	3.81	233
Mt. Bohyun (820 m)	3.57	234
Mt. Bisul (1,000 m)	1.59	256
Mt. Bohyun (1,000 m)	1.50	257
Hyper-K (Tochibora, 650 m)	7.55	203
Super-K	1.54	258

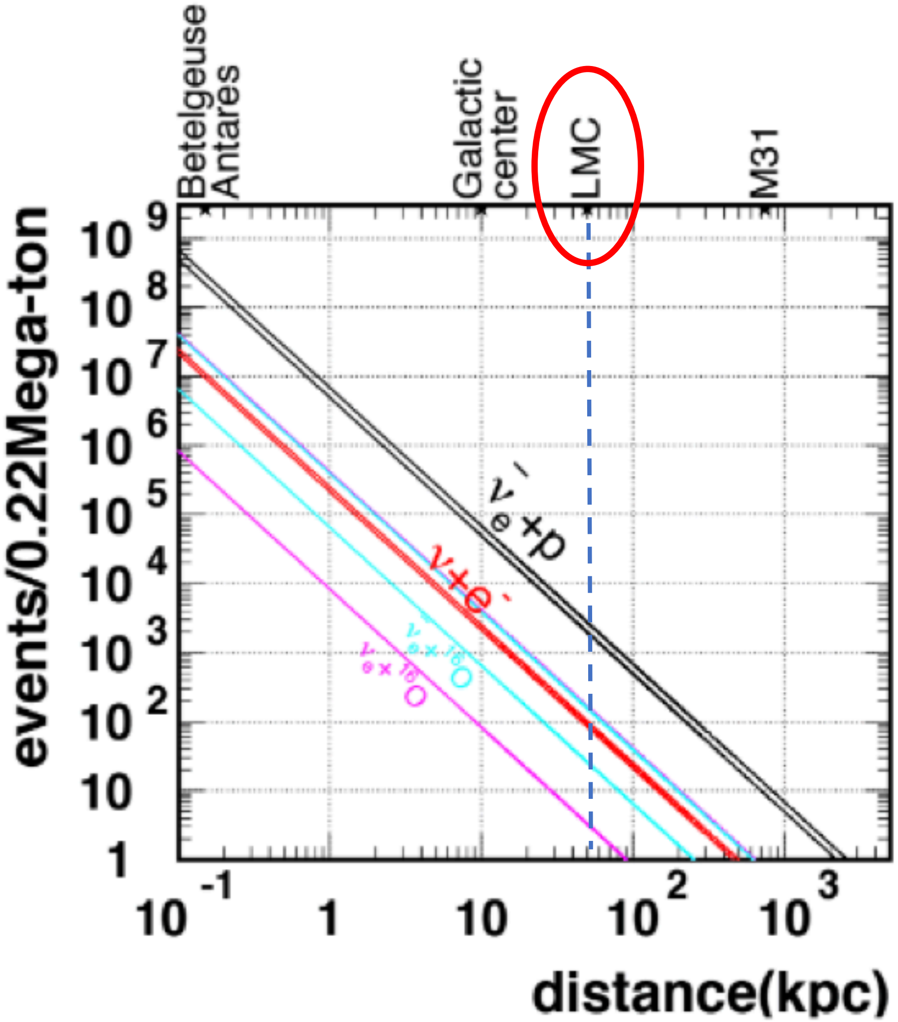




Supernova Burst Neutrinos

SN1987A @LMC

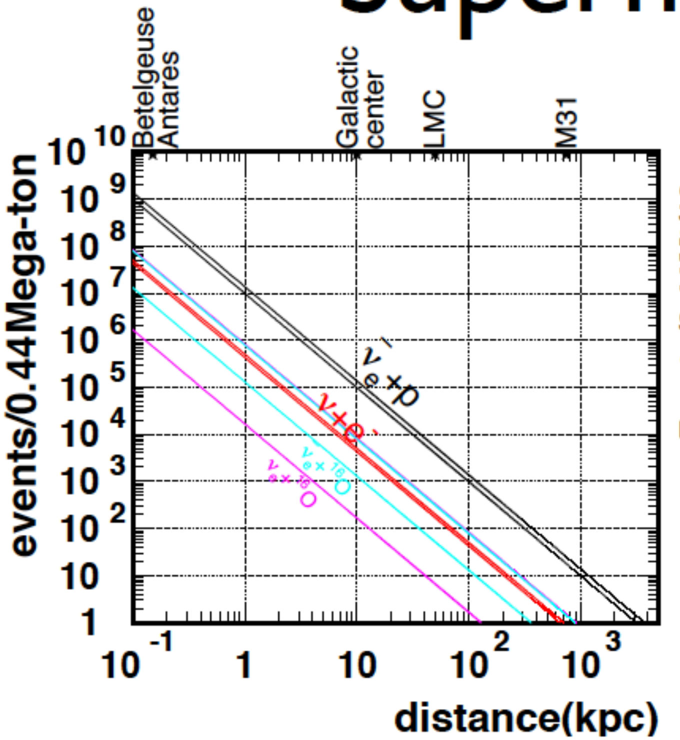


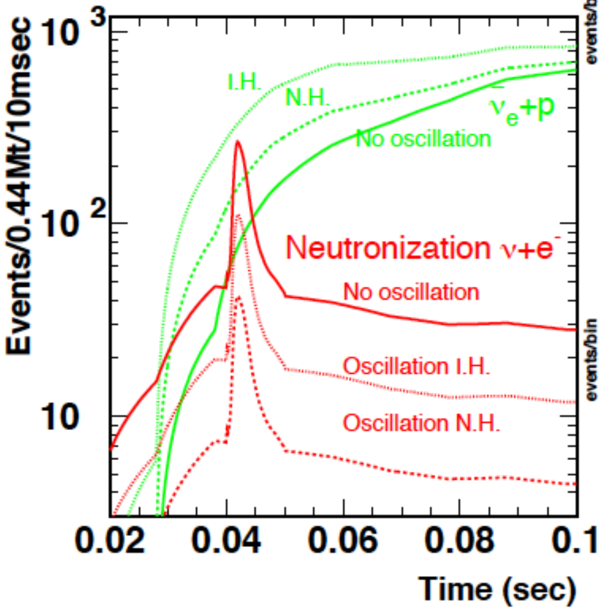


11 events
@Kamiokande

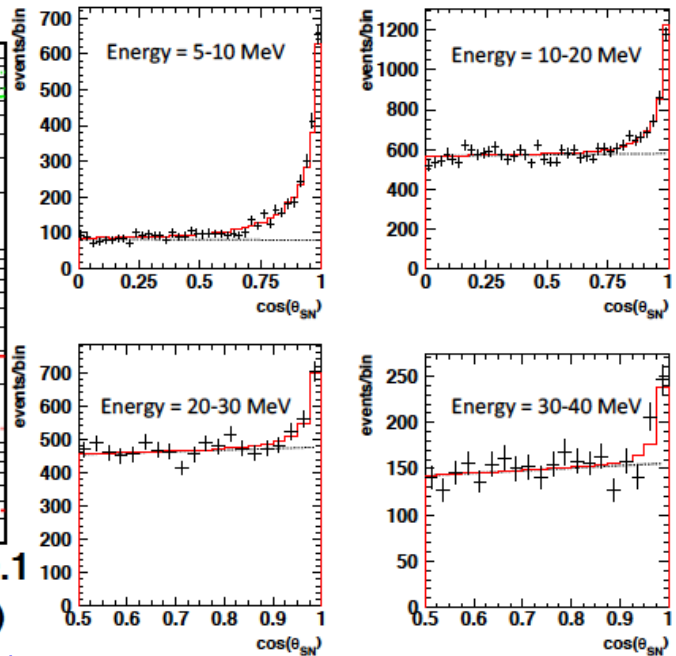
O(1000) events
@Hyper-K/KNO

Supernova burst neutrino





SN explosion mechanism



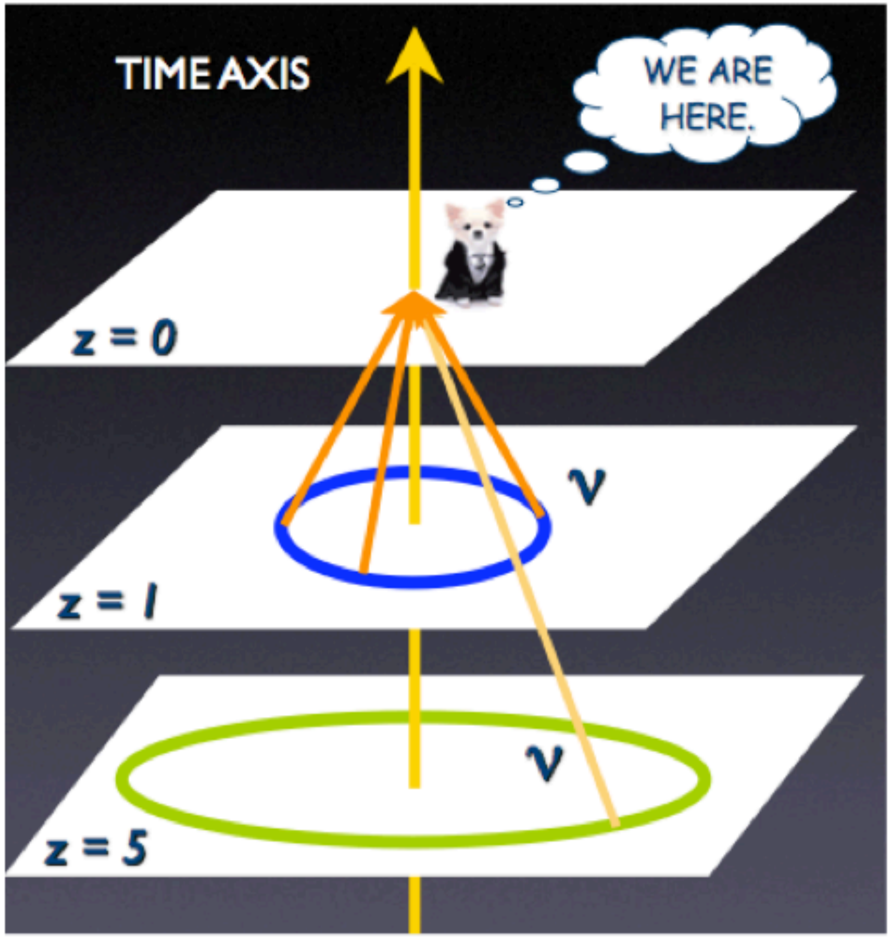
SN directional info.
by ν+e scattering

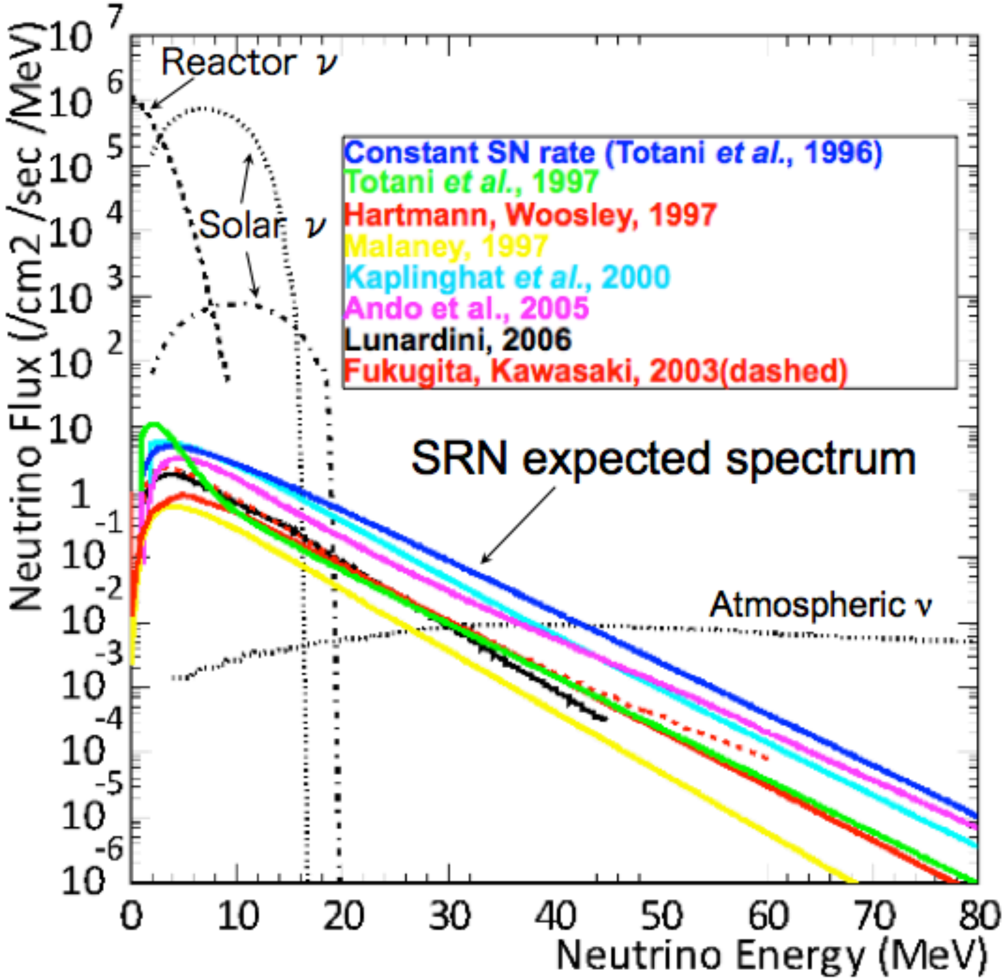
- Large statistics for galactic SN
  - Precise timing and energy information to probe SN mechanism
  - Pointing (2deg@10kpc) and timing for multi-messenger astronomy
- Nearby (>1Mpc) SN
  - Check of dim SN, coincidence with GW telescope, …

Supernova Relic Neutrinos (SRN)

Neutrinos emitted from past supernovae

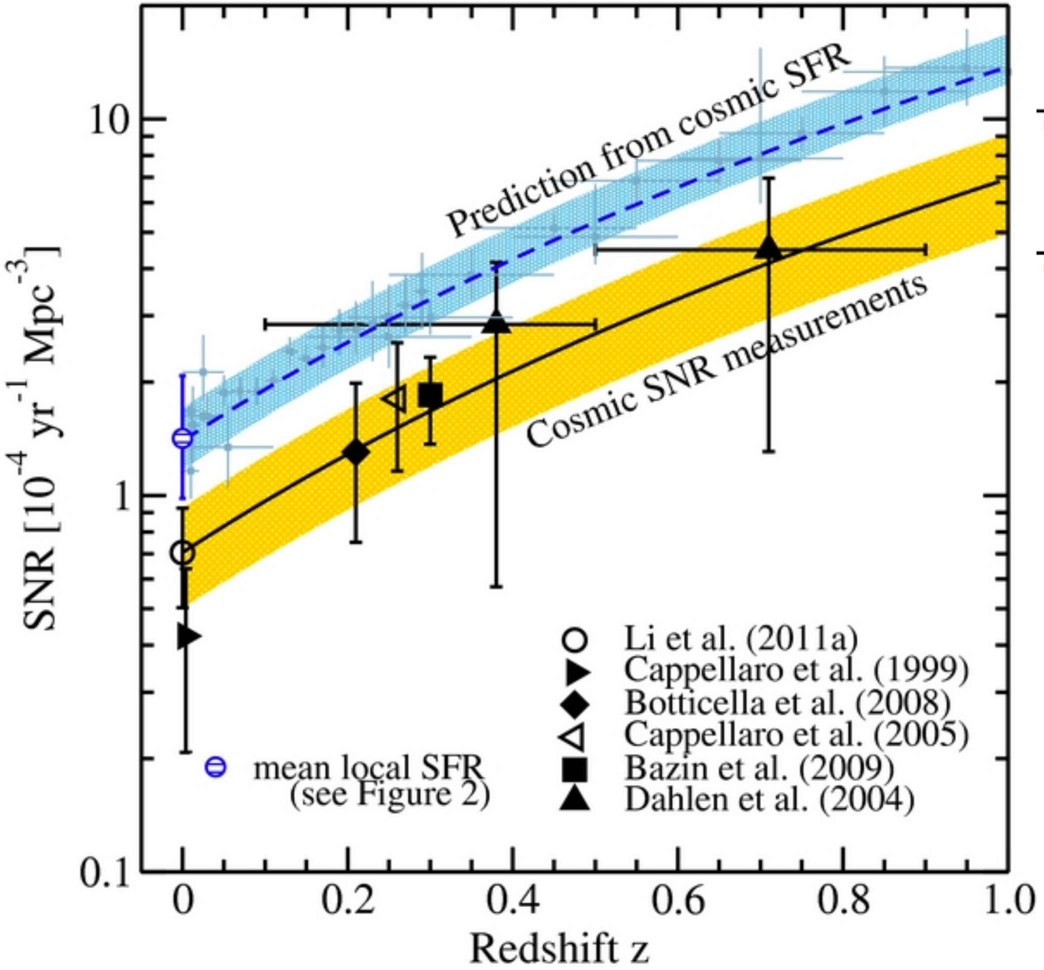
S.Ando



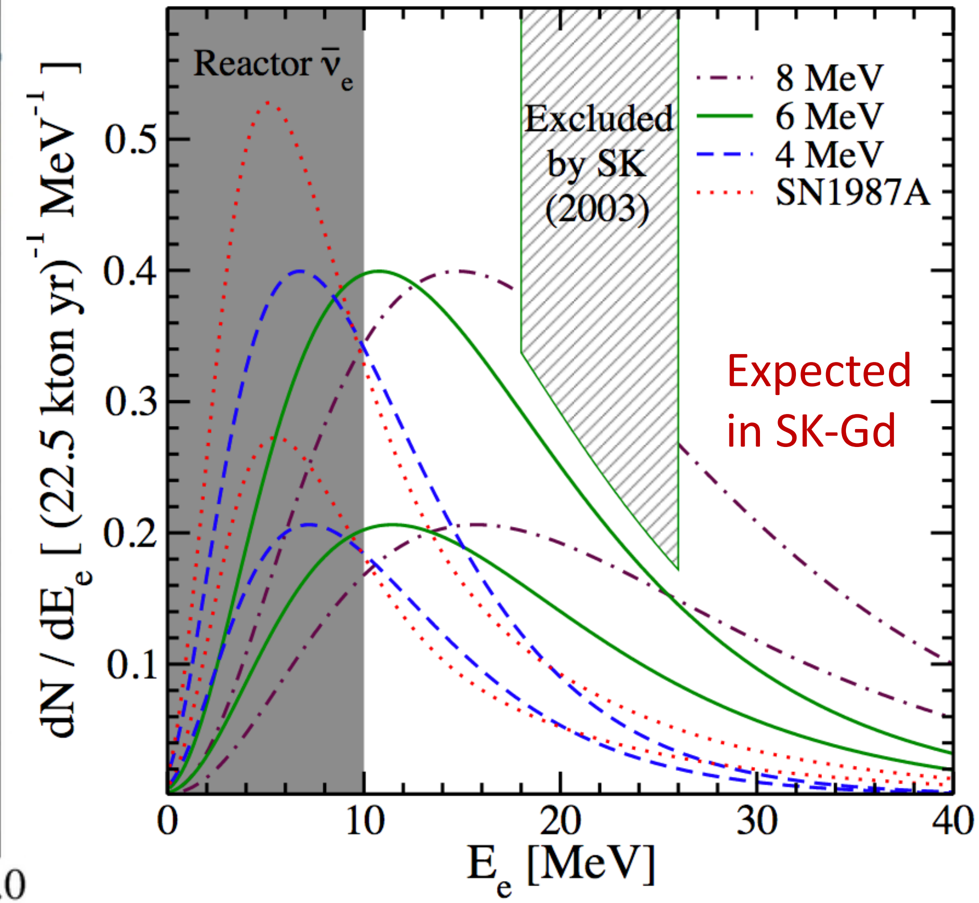


SRN: Physics Motivation

S.Horiuchi et. al (2011)



S.Horiuchi et. al (2009)

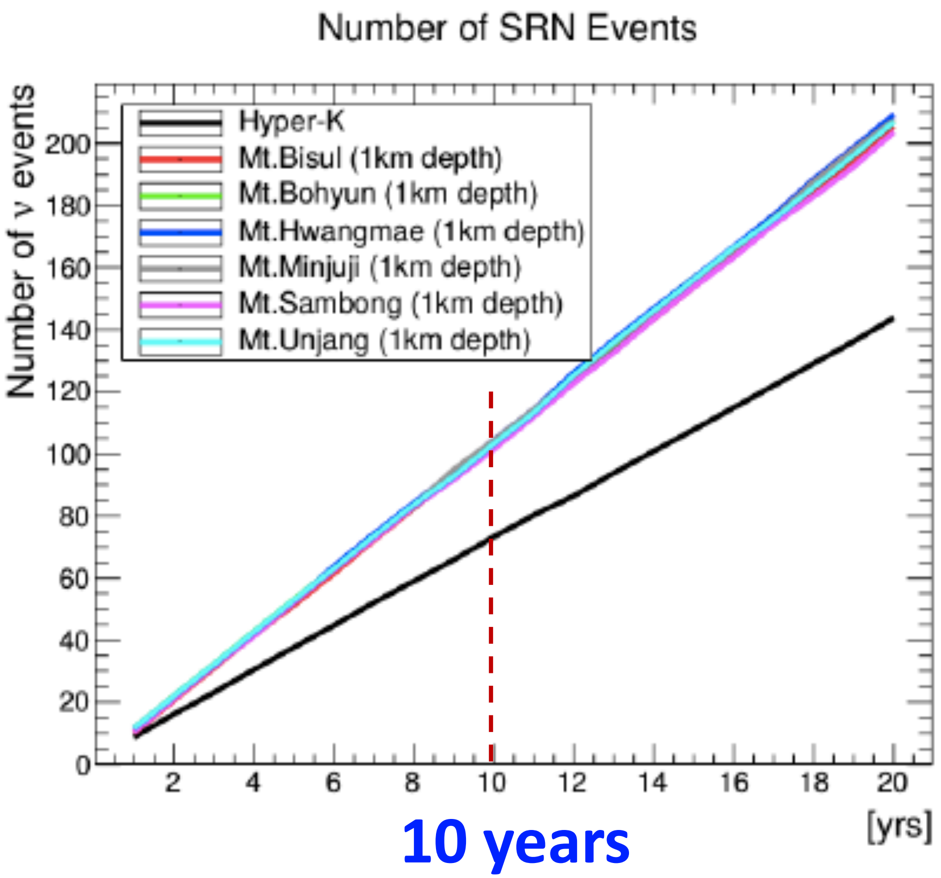


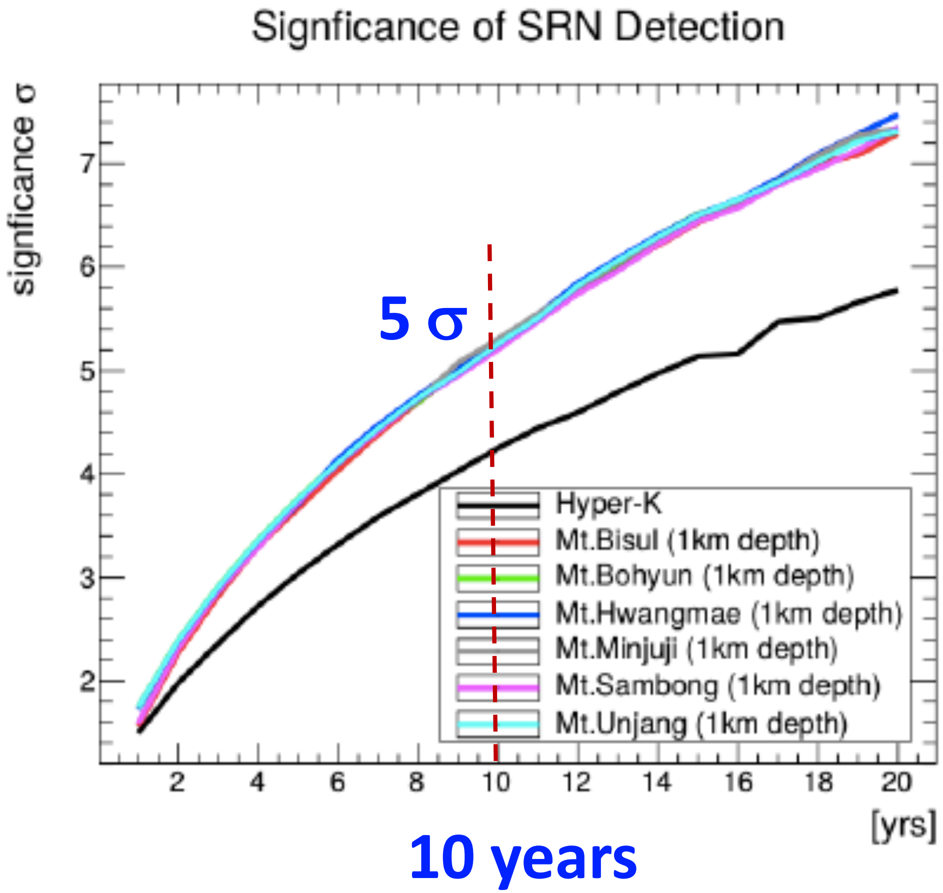
SuperNova Rate problem: ~1.8 ($^{+1.6}_{-0.6}$)

SRN spectrum may solve the supernova rate problem.

Supernova Relic ν (SRN) Sensitivity

- Expected SRN events & significance plot





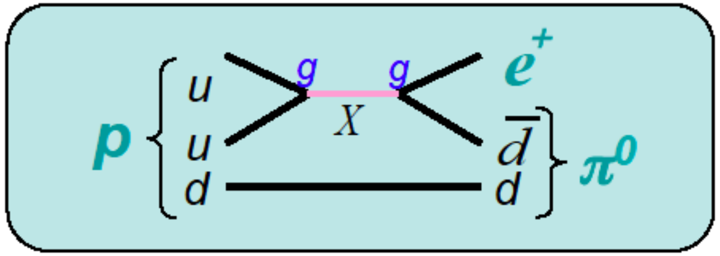
Difference due to 650 m (Japan) vs 1000 m (Korea) overburden

> 6 σ discovery with JD+KD using 10 years data

Proton Decay Search

- Only way to directly probe Grand Unified Theory
- Two major modes predicted by many models

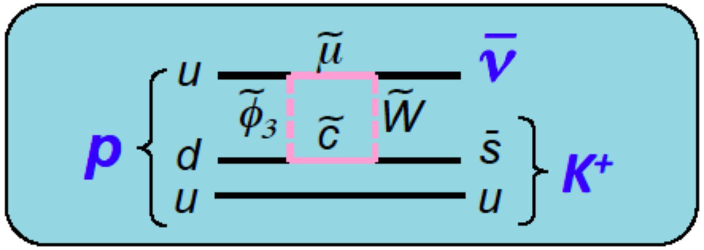
Mediated by gauge bosons



$p \rightarrow e^+\pi^0$

$$\Gamma(p \rightarrow e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated

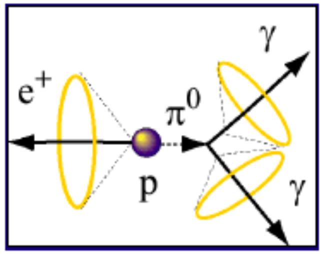


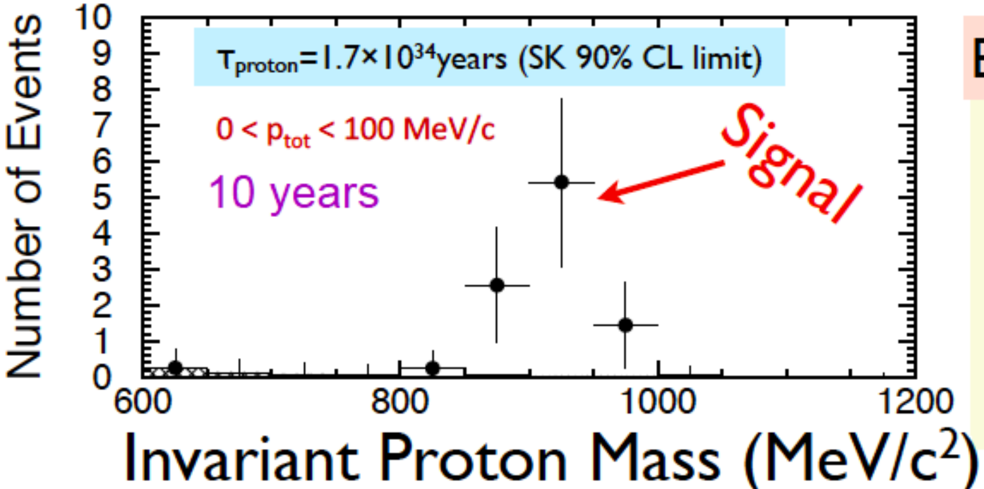
$p \rightarrow \nu K^+$

$$\Gamma(p \rightarrow \bar{\nu} K^+) \sim \frac{\tan^2 \beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

- Need broad searches including other possible modes

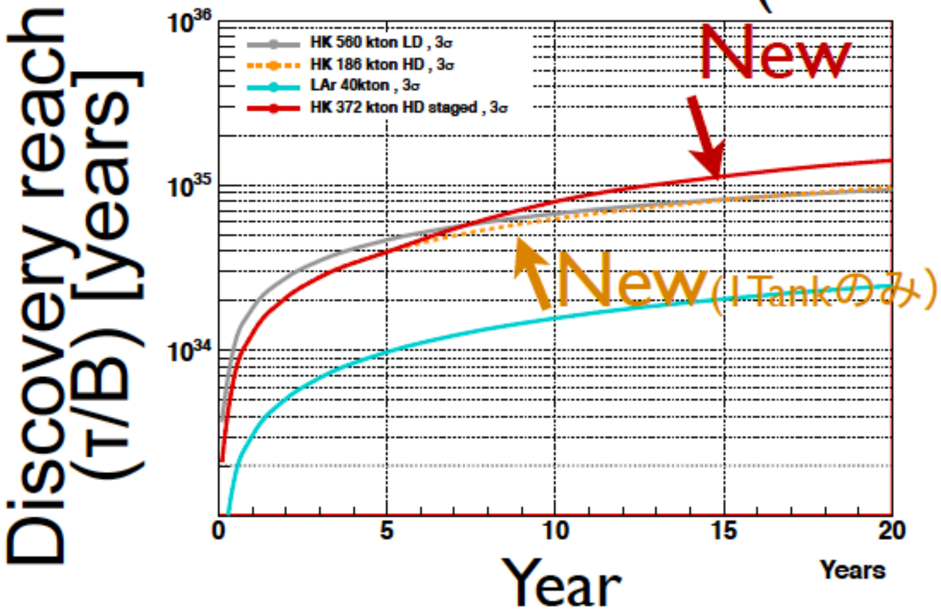
$p \to e^+\pi^0$ search in Hyper-K





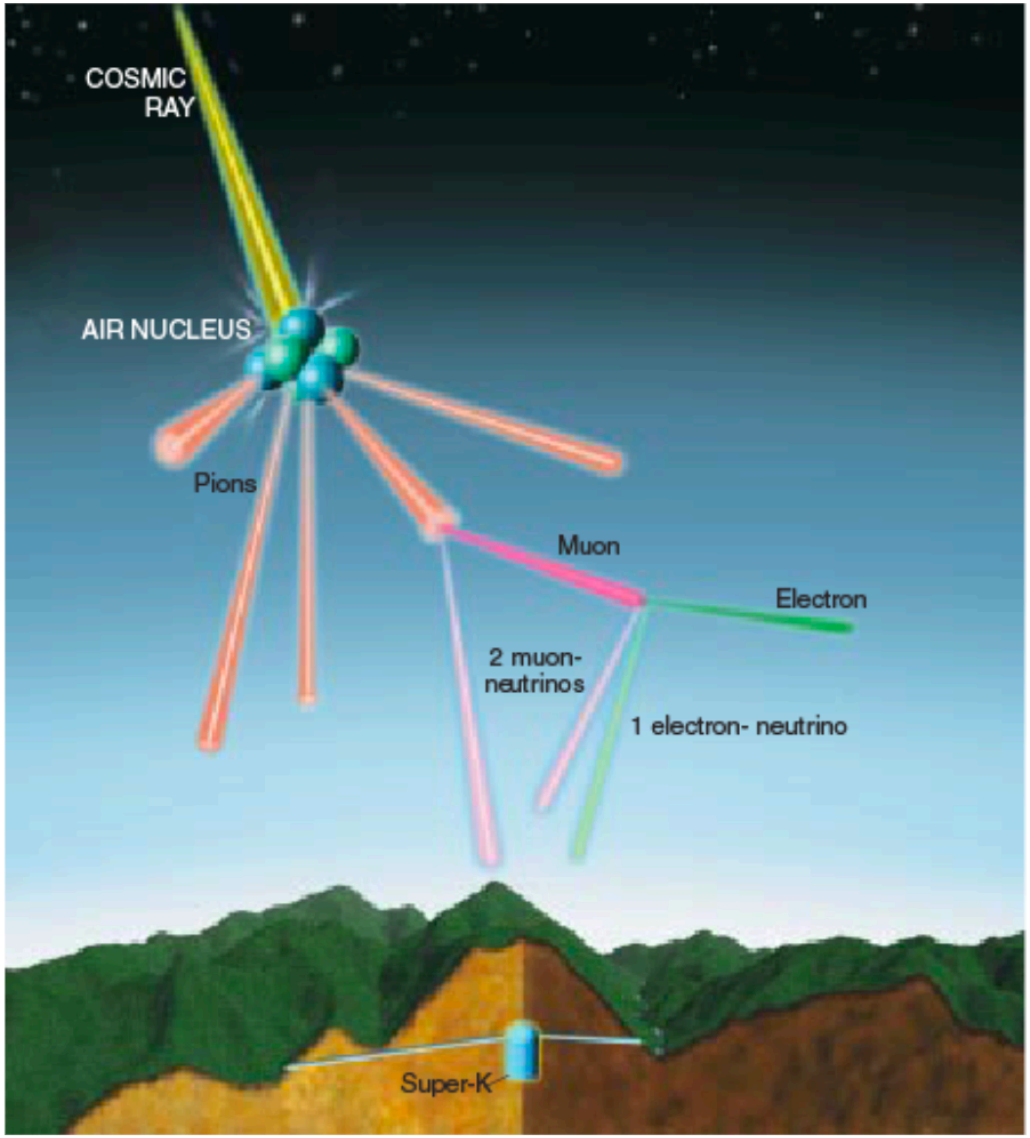
BG free by high-sensitive PMTs

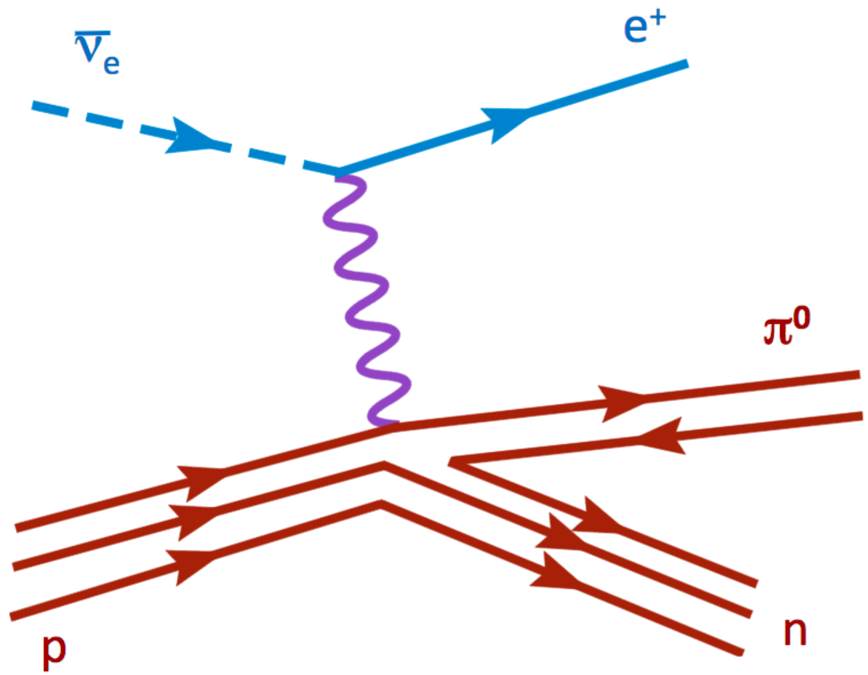
For the case of
τ_{proton}= 1.4×10^{34}years
(Super-K limit)
~9σ discovery@HK



- Only realistic proposal to reach to 10^{35} years@3σ

Background: Atmospheric Neutrinos

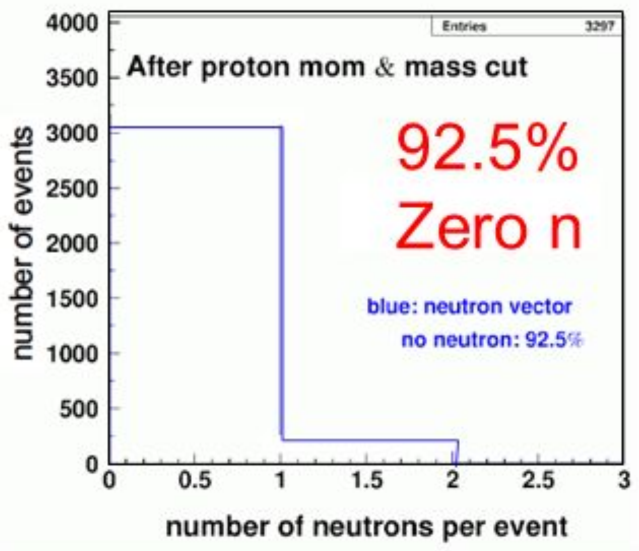




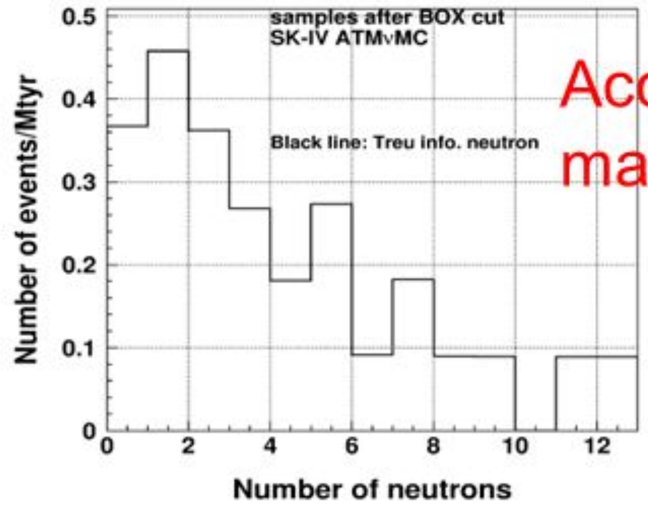
Improvement for Proton decay w/ Gd

Neutron multiplicity for

$P \rightarrow e^+\pi^0$ MC



Atmospheric ν BG



Accompany many n

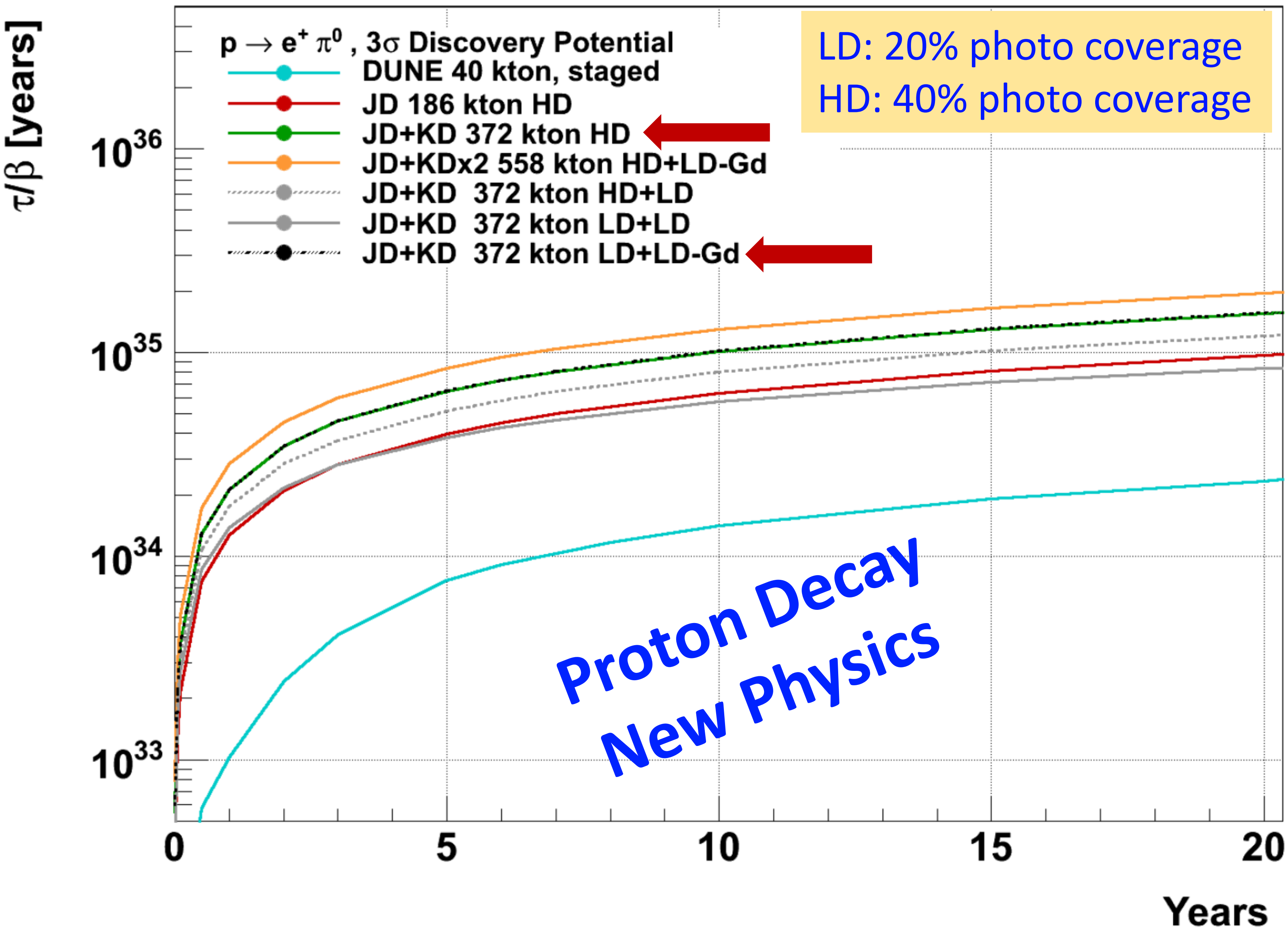
If one proton decay event is observed at Super-K after 10 years

Current background level: 0.58 events/10 years

Background with neutron anti-tag: 0.098 events/10 years

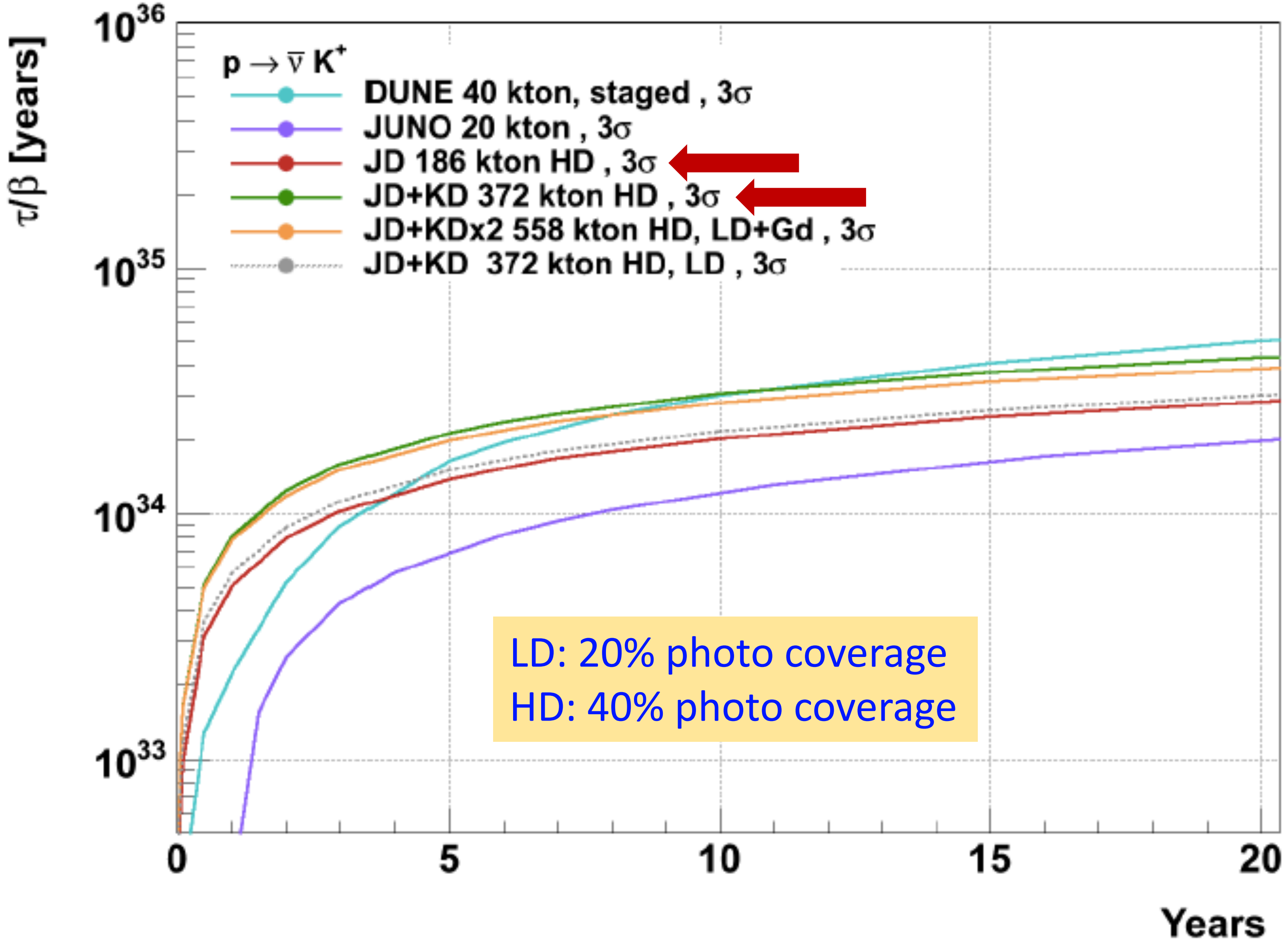
Background probability will be decreased from 44% to 9%.

Discovery Potential for p -> $e^+\pi^0$



- This mode's efficiency does not depend much on cathode coverage above 20%
- Background reduction though is improved by Gd loading

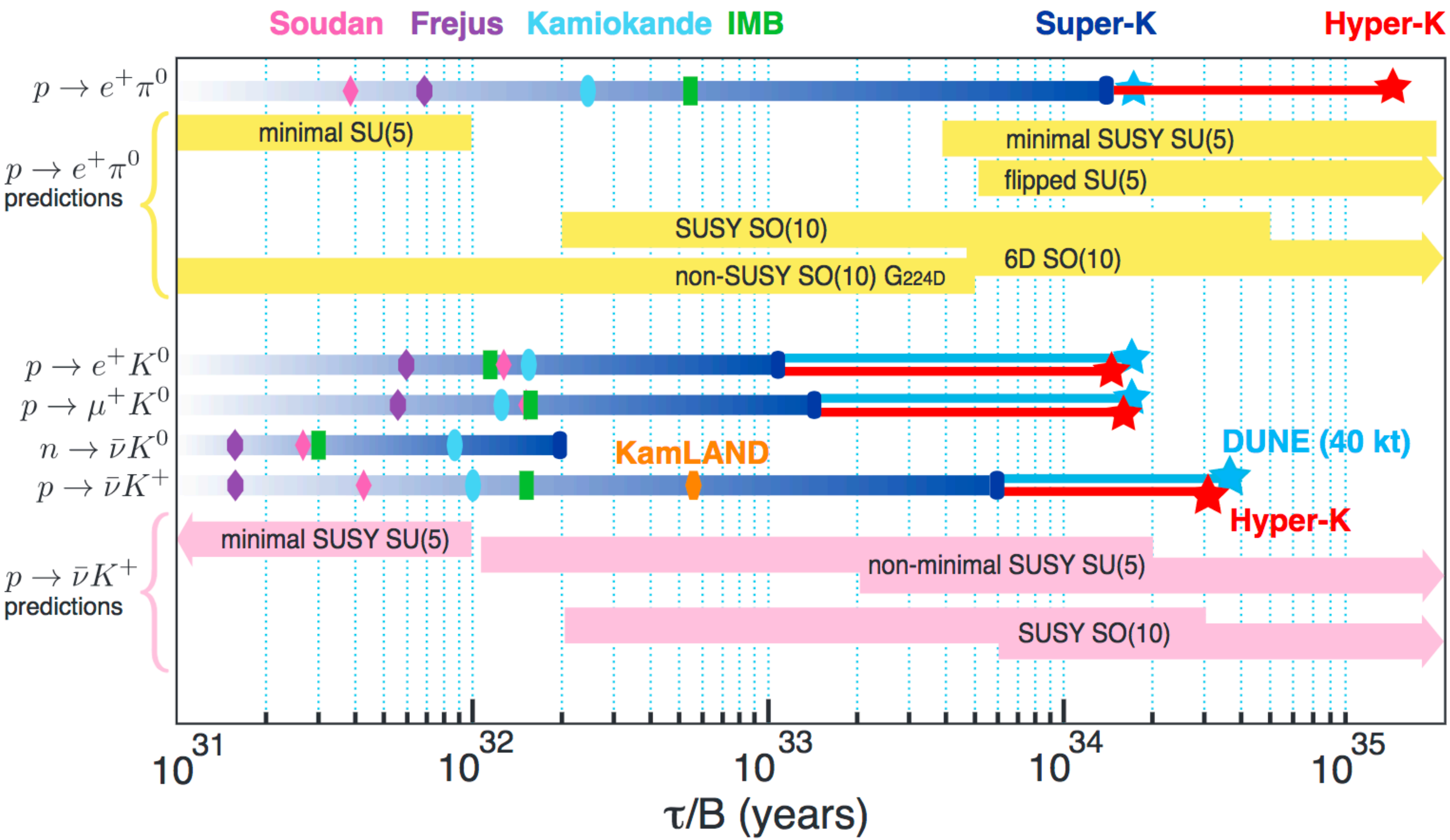
Discovery Potential for p -> νK^+



- Efficiency depends considerably on coverage
- Background reduction is improved by Gd loading

Proton Decay Limits & Sensitivities

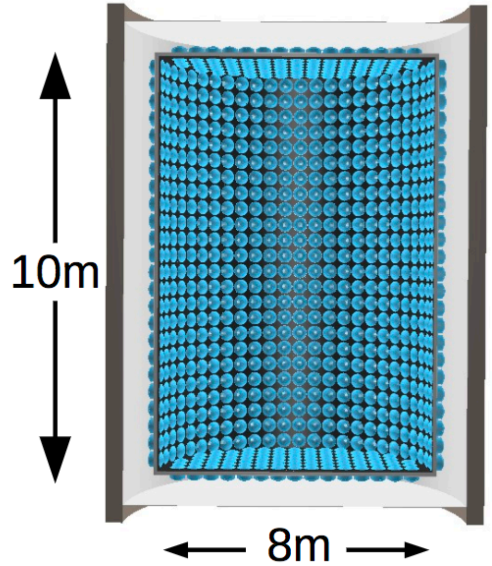
Only way to directly probe GUT

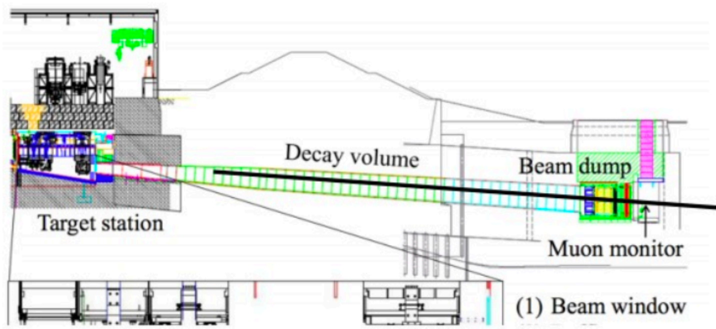


Intermediate WCD (E61)

International Effort to reduce syst. error of HK

- Hyper-Kamiokande limited by systematics, not neutrino statistics
- E61 intermediate detector:
  - Kilo-ton scale water Cherenkov detector
  - Located ~1km from neutrino production point
  - Same technology as far detector
    - Increased cancellation of systematics
  - Measure neutrino beam at different off-axis angles



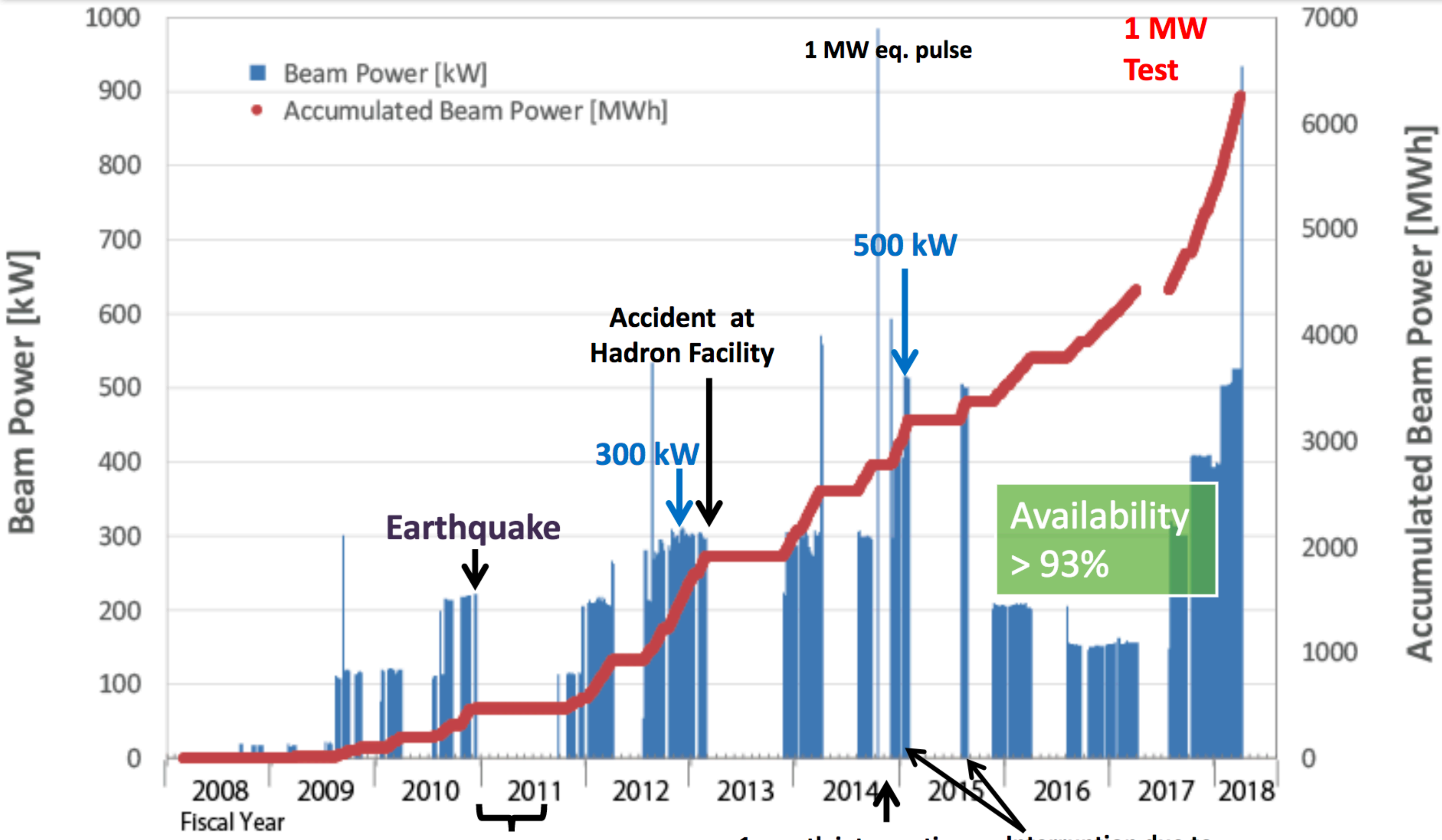


~1 km baseline

1-4° off-axis angle

- 500 mPMT
- Gd loading
- Site will be selected soon.

Beam Power History at MLF



~10 months interruption due to the earthquake

~1 month interruption due to the fire in MLF

Interruption due to troubles of Hg-target

as of July 3, 2018

Saito-san's talk

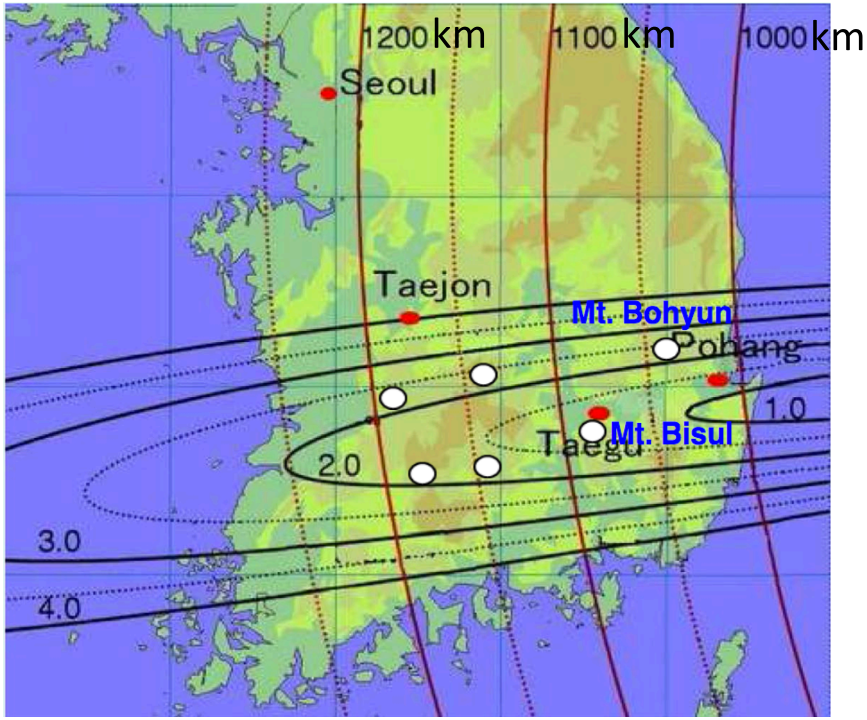
Some candidate sites in Korea

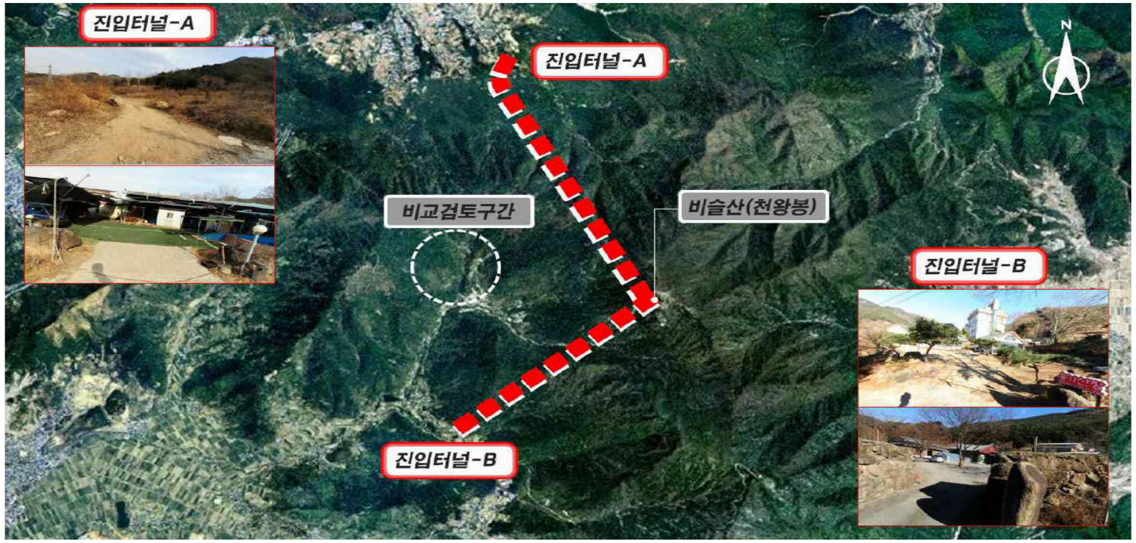
Site candidates for a 2nd osc. maximum detector in Korea

-- Baselines with 1,000~1,200 km
-- 2.0~2.5^{o} or 1.5~2.0^{o} off axis beam directions
-- >1,000 m high mountains with hard granite rocks

Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	**~1.3^{o}**	**1088 km**	**1084 m**
Mt. Hwangmae	~1.8^{o}	1140 km	1113 m
Mt. Sambong	~1.9^{o}	1180 km	1186 m
Mt. Bohyun	**~2.2^{o}**	**1040 km**	**1126 m**
Mt. Minjuii	~2.2^{o}	1140 km	1242 m
Mt. Unjang	~2.2^{o}	1190 km	1125 m

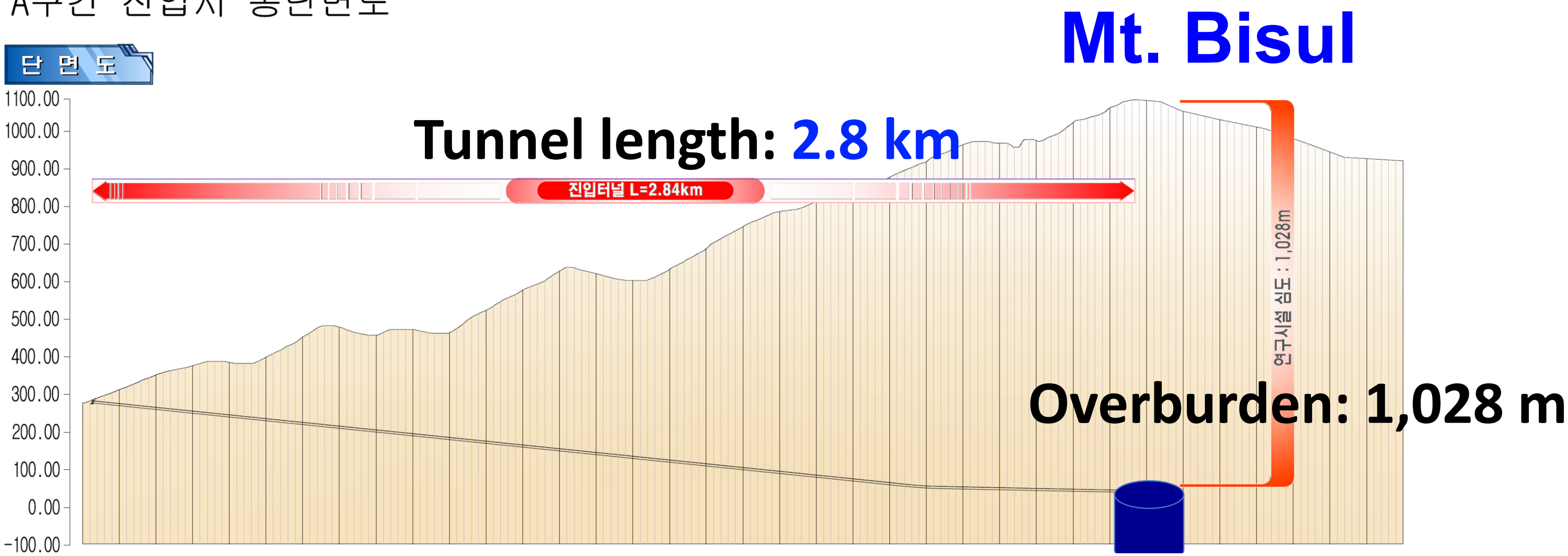
Mt. Bisul Site

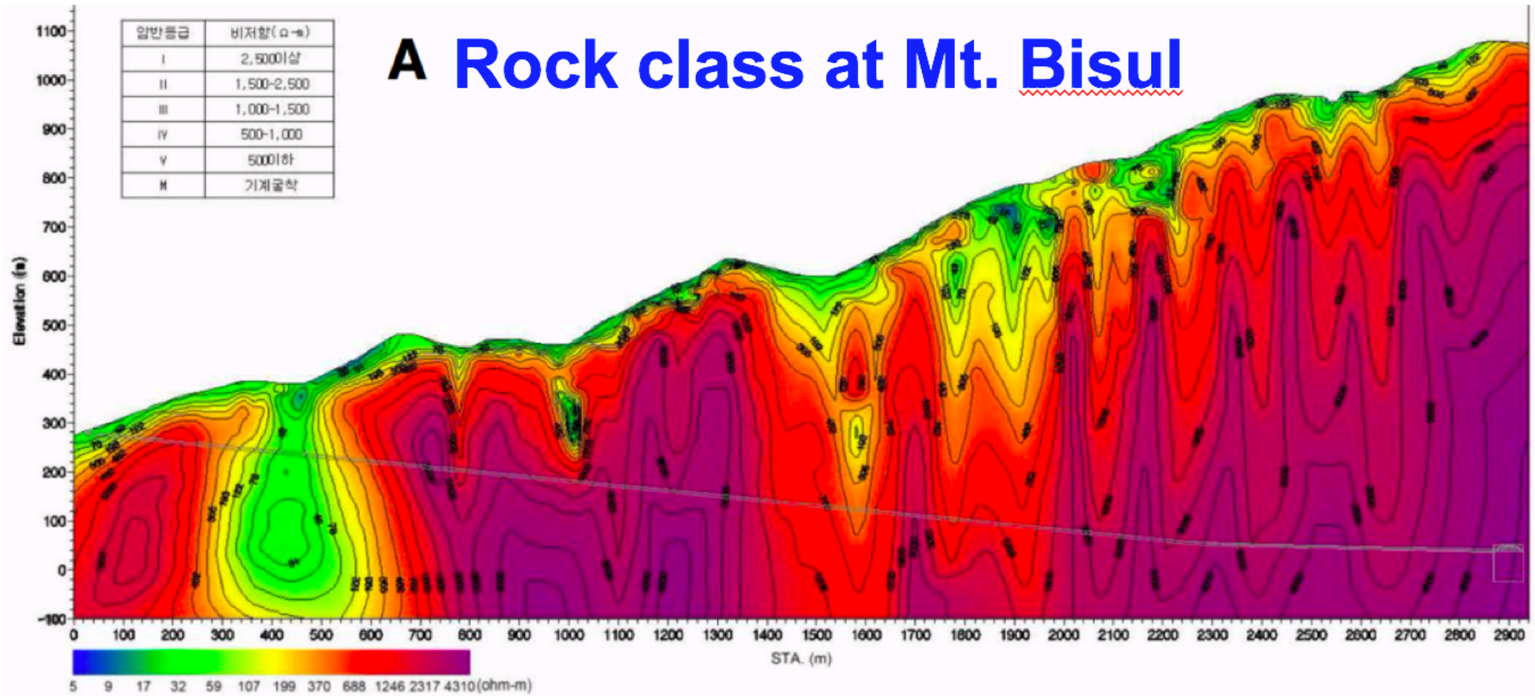




Mt. Bisul Site

A구간 진입시 종단면도

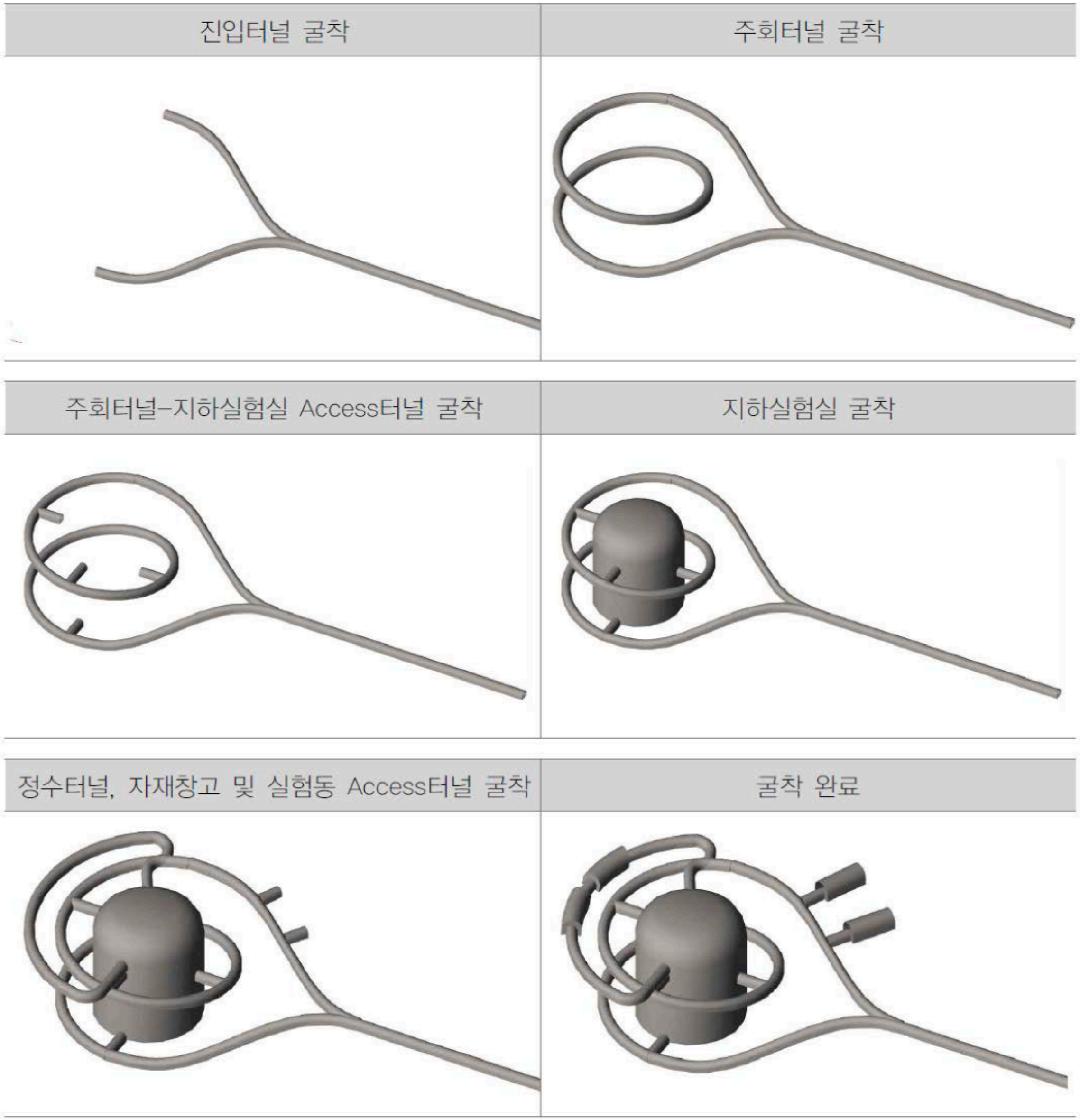




암반등급	비저항(Ω-m)
I	2,500이상
II	1,500-2,500
III	1,000-1,500
IV	500-1,000
V	500이하
M	기계굴착

Experimental Hall (Cavern) Construction

10.3.3 지하실험실구간 시공순서



T2HKK Detector Options

- ❑ Twice bigger detector w/ less photo coverage?
- ❑ Gd loading ? (proton decay, SRN)
- ❑ Water-based Liquid Scintillator?
- ❑ PMT options:
  - 20 inch PMT
  - mPMT
  - SiPM etc..

→ We need sensitivity studies/R&D/detector design.
→ You have lots of opportunities in T2HKK/KNO !

Huge opportunities for new international collaborators !

Join us !

WbLS Detector at Yemilab

Good demonstrator for T2HKK

arXiv:1903.05368

Neutrino Telescope at Yemilab, Korea

Seon-Hee Seo*

Center for Underground Physics,

Institute for Basic Science,

55 Expo-ro Yuseong-gu, Daejeon 34126, Korea

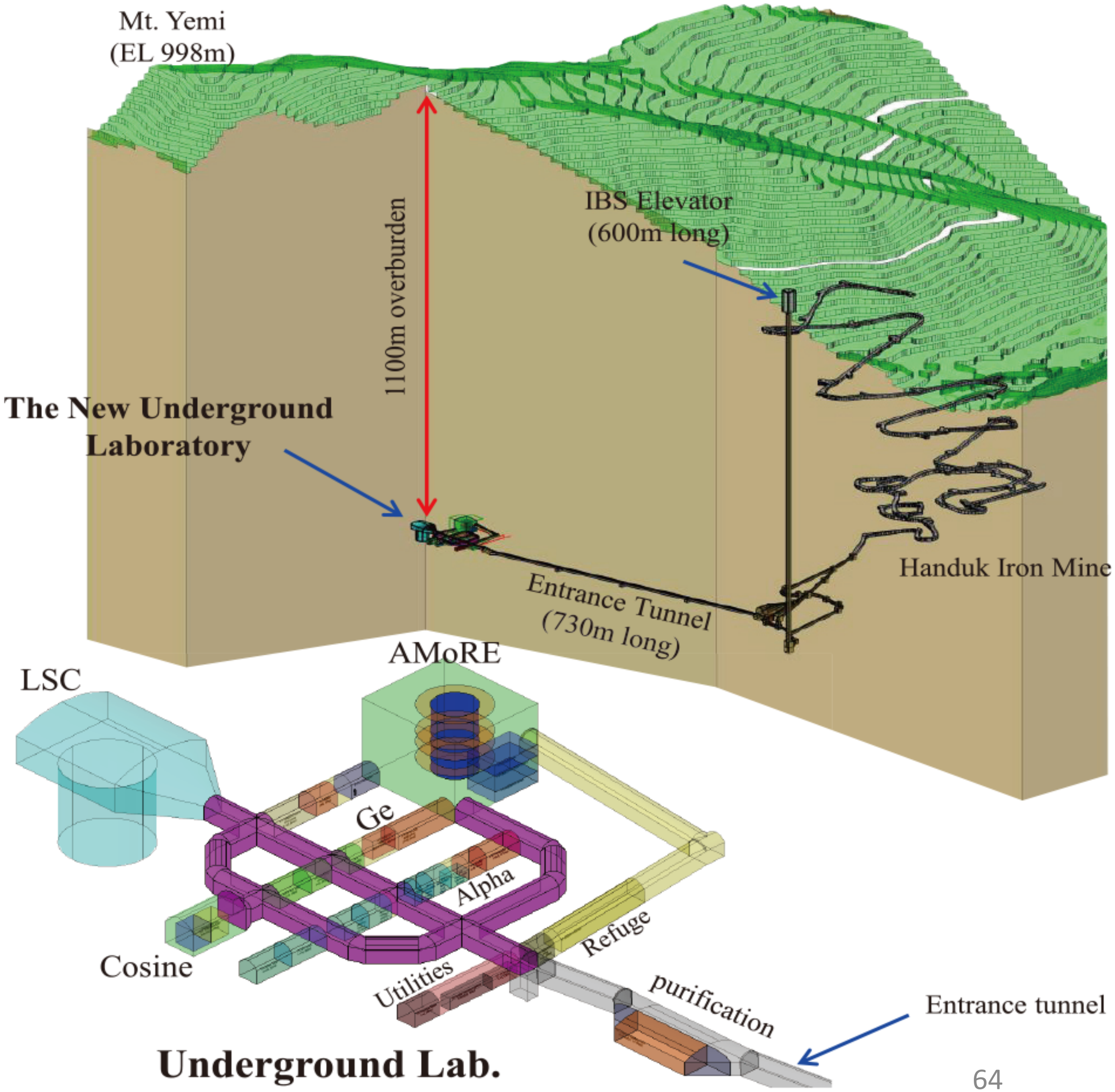
(Dated: March 13, 2019)

A new underground lab, Yemilab, is being constructed in Handuk iron mine, Korea. The default design of Yemilab includes a space for a future neutrino experiment. We propose to build a water-based liquid scintillator (WbLS) detector of 4∼5 kiloton size at the Yemilab. The WbLS technology combines the benefits from both water and liquid scintillator (LS) in a single detector so that low energy physics and rare event searches can have higher sensitivities due to the larger size detector with increased light yield. No experiment has ever used a WbLS technology since it still needs some R&D studies, as currently being performed by THEIA group. If this technology works successfully with kiloton scale detector at Yemilab then it can be applied to future T2HKK (Hyper-K 2^{nd} detector in Korea) to improve its physics potentials especially in the low energy region.

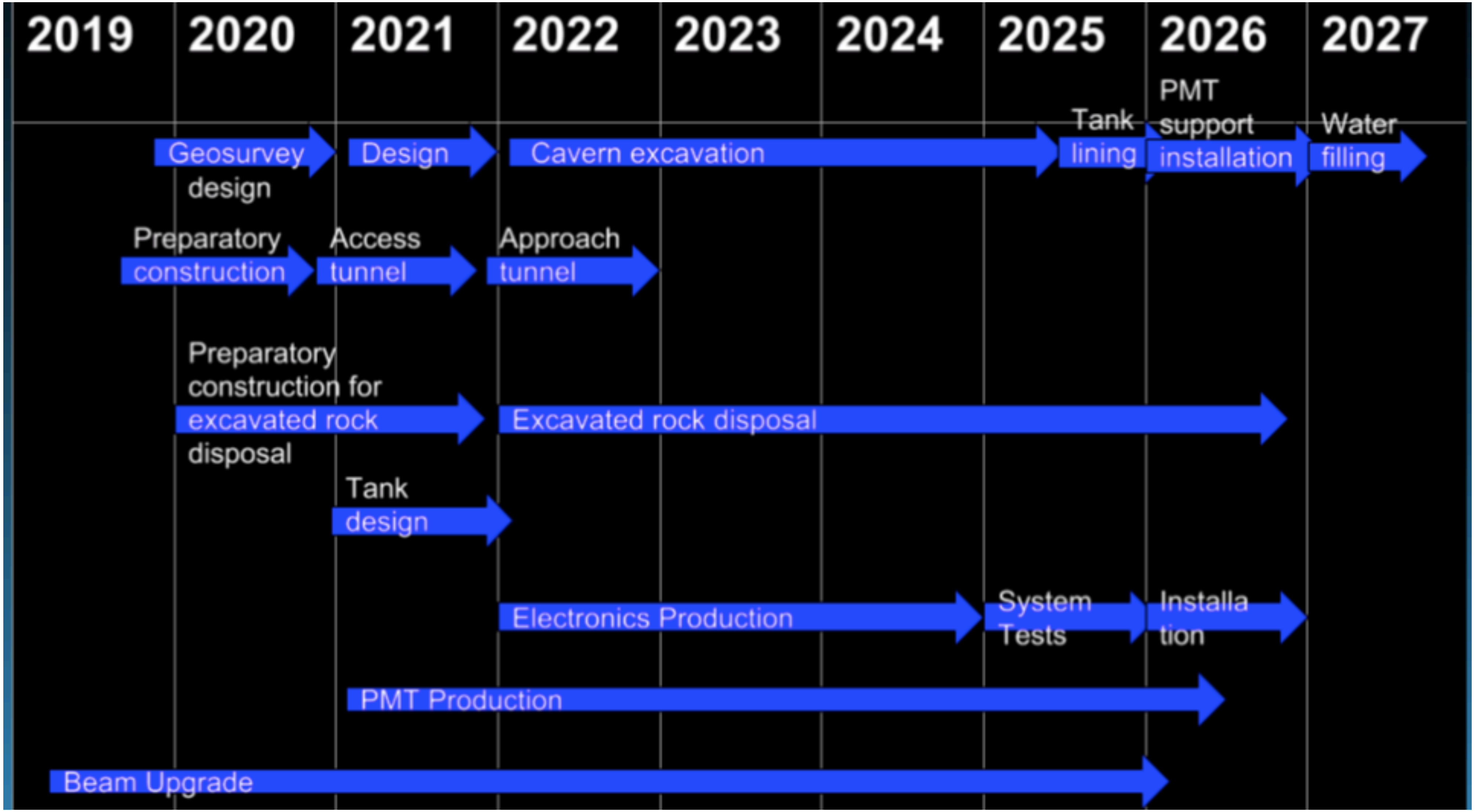
Yemilab @Handuk iron mine

~1 km depth

To be completed
at the end of 2020



Hyper-K Construction Plan



Summary

❑ Hyper-K: next generation multi-purpose ν experiment.

2 x 260 kton water detectors MeV – TeV

❑ Physics sensitivities are improved w/ the 2nd detector in Korea.

- Neutrino mass ordering determination
- CPV, CP precision, CP coverage
- Non-standard ν interaction
- Solar/SRN etc…

❑ World class discoveries are expected to be made.

CPV, SN/SRN, proton decay etc…

❑ Construction of the 1st detector in Japan starts in April 2020.

❑ Site survey is done for T2HKK → very promising results